様　式　Ｃ－１９、Ｆ－１９、Ｚ－１９　（共通）

# 科学研究費助成事業　　研究成果報告書

平成 ２７ 年　７ 月　６ 日現在

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研究課題名（和文）超伝導量子ビットを用いた量子情報処理

研究課題名（英文）Quantum information processing using superconducting qubits

研究代表者
NORI　FRANCO（NORI, FRANCO）

独立行政法人理化学研究所・創発物性科学研究センター・グループディレクター

研究者番号：５０４１５２６２

交付決定額（研究期間全体）：（直接経費）　62,800,000円

研究成果の概要（和文）：人工原子としての超伝導量子ビットに関する研究を行い、自然にある原子に対するものと類似した問題を追及しました。巨大人工原子がどのように、光、伝搬路，電磁的共振器，機械的共振器等と相互作用するか、という課題を含み、量子光学、原子物理、固体物理、ナノサイエンス、コンピューターサイエンスに及ぶ、分野横断的な理論的研究を行い、その研究成果は物理学のトップレベルのジャーナルに掲載されました。

研究成果の概要（英文）：We studied superconducting (SC) qubits as “Artifical Atoms” and asked similar questions researchers have asked for natural atoms (including how these “giant atoms” interact with light, transmission lines, electro-magnetic resonators, mechanical resonators, etc.). We theoretically studied the interdisciplinary field involving quantum optics, atomic physics, condensed matter physics, nanoscience, and computer science. These types of problems include how photons interact with qubits, lasing phenomena using superconducting qubits; single-photon generators; photon-number control (Fock state generation); coupling qubits by a resonator; coupling resonators by a qubit; and also quantum measurements. This is a growing interdisciplinary area of research. We obtained many interesting results, which were featured in top physics journals.

研究分野：理論物理学

キーワード：Artificial Atoms　Quantum nano-devices　Superconducting qubits　Inter-disciplinary　Heterogeneous　Hysbrid quantum circuits　Computational studies

## 31．研究開始当初の背景 【Initial Background of the Research】

The study of "Artifical Atoms", including superconducting (SC) qubits is exploding, due to its intrinsic fundamental interest and for potential applications. The interdisciplinary field which we helped to develop (involving quantum optics, atomic physics, condensed matter physics, nanoscience, and computer science) is attracting considerable interest. These types of problems include how photons interact with qubits, lasing phenomena using superconducting circuits; single-photon generator; photon-number control (Fock state generation); coupling qubits by a resonator; coupling resonators by a qubit; and also quantum measurements. This is a growing interdisciplinary area of research.

## ２．研究の目的 【Research Objectives】

The main purpose of this proposal is to study (superconducting and semiconducting) quantum devices as "Artificial Atoms", and elucidate how these "giant atoms" interact with light, transmission lines, (electro-magnetic or mechanical) resonators, and to use the gained knowledge for designing on-chip hybrid quantum processors, quantum controllers and quantum sensors. We do this through theoretical and computational methods and in close collaboration with experimentalists. We apply the techniques developed in our group for artificial atoms made of superconducting (SC) qubits to semi-conducting devices. We test the developed models and the performance of designed quantum devices through our existing collaborations with ten experimental groups with whom we have already published together. We also continue investigating electron vortex beams and other related topics at the interface with optics, which we pioneered in our group (*PRL* 2007, 2011, *PRX* 2012) and contributed to experimental realizations (*PRL* 2013, *Nat. Phys.* 2013, *Nature Comm.* 2014).

## ３．研究の方法 【Research Method】

Methods used are from atomic physics, quantum optics, condensed matter physics, nanoscience, and quantum information processing. We perform analytical and computational studies, and we collaborate with many experimentalists. We have a track record of very successful interdisciplinary studies.

## ４．研究成果 【Research results】

**"Quantum information processing, quantum hybrid circuits, superconducting qubits"**

Objectives: To better understand quantum hybrid circuits and super-conducting quantum circuits, for quantum information.

We have performed research on various aspects of quantum hybrid circuits and quantum simulators. We propose how to realize high-fidelity quantum storage using a hybrid quantum architecture including two coupled flux qubits and a nitrogen-vacancy center ensemble (NVE). One of the flux qubits is considered as the quantum-computing processor and the NVE serves as the quantum memory. By separating the computing and memory units, the influence of the quantum-computing process on the quantum memory can be effectively eliminated, and hence the quantum storage of an arbitrary quantum state of the computing qubit could be achieved with high fidelity. Furthermore, the present proposal is robust with respect to fluctuations of the system parameters, and it is experimentally feasible with currently available technology.
We propose an experimentally realizable hybrid quantum circuit for achieving a strong coupling between a spin ensemble and a transmission-line resonator via a superconducting flux qubit used as a data bus. The resulting coupling can be used to transfer quantum information between the spin ensemble and the resonator. In particular, in contrast to the direct coupling without a data bus, our approach requires far less spins to achieve a strong coupling between the spin ensemble and the resonator (e.g., three to four orders of magnitude less). This proposed hybrid quantum circuit could enable a long-time quantum memory when storing information in the spin ensemble, and allows the possibility to explore nonlinear effects in the ultrastrong-coupling regime.

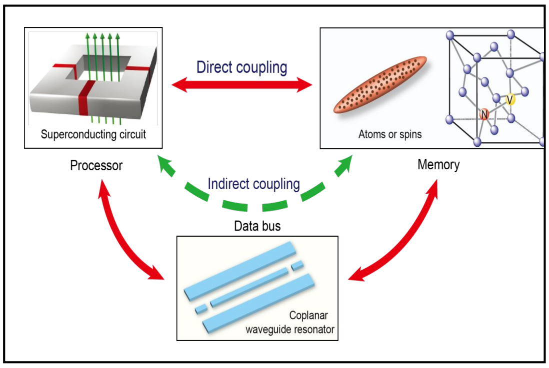


Fig. 1: Schematic diagram showing how to construct a hybrid quantum processor via a quantum data bus or "bridge" (indirect coupling) or without any intermediary (direct coupling). For fast and robust operations, superconducting circuits can serve as the processor; for long coherence times, atomic (or spin) systems can play the role of the memory in a hybrid quantum system. In the direct-coupling case, superconducting qubits couple with atoms (or spins) via electromagnetic fields. In the indirect-coupling case, a quantum resonator (e.g., coplanar waveguide resonator) acts as a data bus to transfer (quantum) information between the two components of the hybrid quantum system.

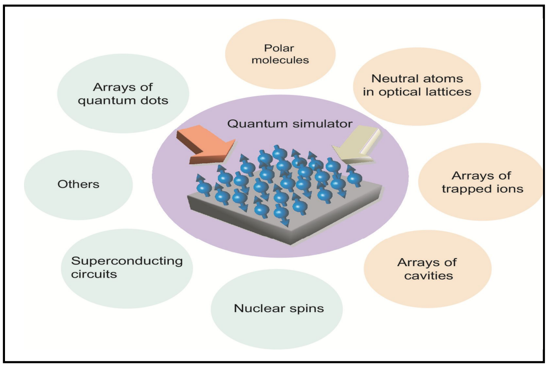


Fig. 2: Quantum Simulator (from our Jan 2014 cover of Reviews of Modern Physics)

**A few selected publications on this topic:**

Z.-L. Xiang, S. Ashhab, J.Q. You, F. Nori, *Hybrid quantum circuits: Superconducting circuits interacting with other quantum systems*, Rev. Mod. Phys. **85**, 623 (2013). Top 0.02% cited paper in 2013.

X.-Y. Lu, Z.-L Xiang, W. Cui, J.Q. You, F. Nori, *Quantum memory using a hybrid circuit with flux qubits and NV centers*, Phys. Rev. A **88**, 012329 (2013).

Z.-L. Xiang, X.-Y. Lu, T.-F. Li, J.Q. You, F. Nori, *Hybrid quantum circuit consisting of a superconducting flux qubit coupled to a spin ensemble and a transmission-line resonator*, Phys. Rev. B **87**, 144516 (2013).

N. Lambert, C. Flindt, F. Nori, *Photon-mediated electron transport in hybrid circuit-QED*, EPL **103**, 17005 (2013).

I. Georgescu, S. Ashhab, F. Nori, *Quantum Simulation*, Rev. Mod. Phys. 86, 153 (2014). Cover story of RMP.

**"Optomechanics: coupling optical and mechanical degrees of freedom"**

Objective: Cavity optomechanical systems can provide a natural platform to induce an interaction between mechanical resonators because there is an intrinsic coupling mechanism between optical and mechanical degrees of freedom. We are currently studying several aspects of this growing area of nanoscience.

We proposed a spectrometric method to reconstruct the motional states of mechanical modes in optomechanics [1]. We also obtained exact analytical solutions to study the coherent interaction between a single photon and the mechanical motion of a membrane in quadratic optomechanics [2]. We proposed a simple method [3] to generate quantum entanglement between two macroscopic mechanical resonators in a two-cavity optomechanical system. Moreover, we proposed how to achieve a steady-state mechanical squeezing in an optomechanical system via a Duffing nonlinearity [4].
We investigated [5] the nonlinear interaction between a squeezed cavity mode and a mechanical mode in an optomechanical system (OMS) that allows to selectively obtain either a radiation-pressure coupling or a parametric-amplification process. We also proposed and analyzed circuits [6,7] that implement nonlinear couplings between super-conducting microwave resonators. These circuits therefore allow for all-electrical realizations of analogs to optomechanical systems, with couplings that can be both strong and tunable [6,7].

**A few selected publications on this topic:**

[1] J.Q. Liao, F. Nori, Spectrometric Reconstruction of Mechanical-motional

States in Optomechanics, Phys. Rev. A 90, 023851 (2014).
[2] J.Q. Liao, F. Nori, Single-photon quadratic optomechanics, Scientific Reports 4, 6302 (2014).
[3] J.-Q. Liao, Q.-Q. Wu, F. Nori, Entangling two macroscopic mechanical mirrors in 2-cavity optomechanics, Phys. Rev. A 89, 014302 (2014).
[4] X.Y. Lu, J.Q. Liao, L. Tian, F. Nori, Steady-state Mechanical Squeezing in an Optomechanical System with Nonlinearity, Phys. Rev. A 91, 013834 (2015).
[5] X.Y. Lu, Y. Wu, J.R. Johansson, H. Jing, J. Zhang, F. Nori, Squeezed Optomechanics with Phase-matched Amplification and Dissipation, Phys. Rev. Lett. 114, 093602 (2015).
[6] J.R. Johansson, G. Johansson, F. Nori, Optomechanical-like coupling between superconducting resonators, Phys. Rev. A 90, 053833 (2014).
[7] E. Kim, J.R. Johansson, F. Nori, Circuit analog of quadratic optomechanics, Phys. Rev. A 91, 033835 (2015).

"Parity-Time (PT) Symmetric Photonics"

Objective: Optical systems with balanced loss and gain provide a unique platform to implement classical analogues of quantum systems described by non-Hermitian parity–time (PT)-symmetric Hamiltonians. Such systems can be used to create synthetic materials with properties that cannot be attained in materials having only loss or only gain. Our results could lead to a new generation of synthetic optical systems enabling on-chip manipulation and control of light propagation.

We report PT-symmetry breaking in coupled optical resonators. We observed non-reciprocity in the PT-symmetry-breaking phase due to strong field localization, which significantly enhances nonlinearity. We show [1] that in one direction there is a complete absence of resonance peaks whereas in the other direction the transmission is resonantly enhanced. Our results [1] could lead to a new generation of synthetic optical systems enabling on-chip manipulation and control of light propagation.
We show [2] how to turn losses into gain by steering the parameters of a system to the vicinity of an exceptional point (EP), which occurs when the eigenvalues and the corresponding eigenstates of a system coalesce. In our system of coupled microresonators, EPs are manifested as the loss-induced suppression and revival of lasing. Below a critical value, adding loss annihilates an existing Raman laser. Beyond this critical threshold, lasing recovers despite the increasing loss, in stark contrast to what would be expected from conventional laser theory. Our results exemplify the counterintuitive features of EPs and present an innovative method for reversing the effect of loss. We also studied electro-magnetically-induced-transparency in whispering-gallery microcavities [3] and PT-Symmetric phonon lasers [4].

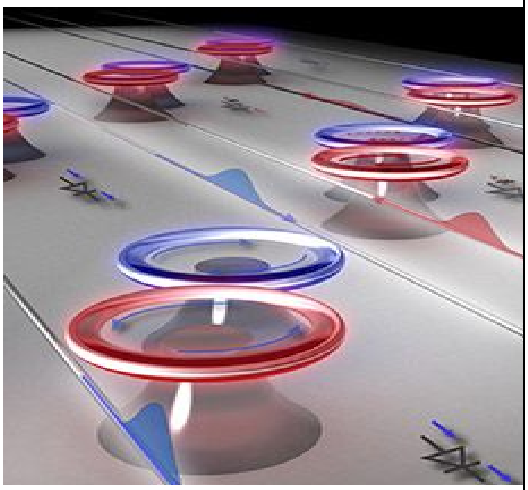

Fig. 1: Our optical diode enables on-chip control of light propagation [1].

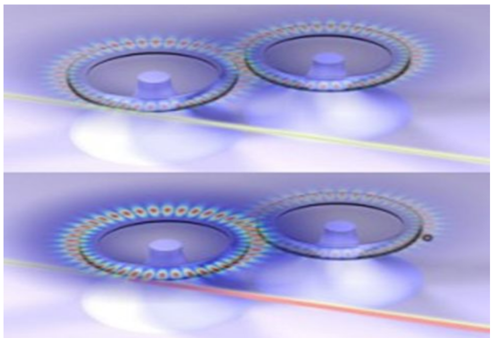

Fig. 2: Extraordinary lasing by increasing energy loss. [2]

**A few selected publications on this topic:**
[1] B. Peng, S. K. Ozdemir, F. Lei, F. Monifi, M. Gianfreda, G. L. Long, S. Fan, F. Nori, C. M. Bender, L. Yang, "Parity-time-symmetric whispering-gallery microcavities", Nature Physics 10, 394-398 (2014). Featured in a Nature Physics "News & Views". Listed as Highly Cited.

[2] B. Peng, S. K. Ozdemir, S. Rotter, H. Yilmaz, M. Liertzer, F. Monifi, C. M. Bender, F. Nori, L. Yang, "Loss-induced suppression and revival of lasing", Science 346, 328-332 (2014). Featured in a "Perspective" in Science (2014).
[3] B. Peng, S.K. Ozdemir, W. Chen, F. Nori, L. Yang, "What is and what is not electromagnetically induced transparency in whispering-gallery microcavities", Nature Commun. 5, 5082 (2014).
[4] H. Jing, S.K. Ozdemir, X.Y. Lu, J. Zhang, L. Yang, F. Nori, PT-Symmetric Phonon Laser, Phys. Rev. Lett. 113, 053604 (2014).

**"Photon trajectories, weak measurements, and spin in evanescent waves"**

Objective: To achieve a better understanding of photonics, optics, and quantum measurements.

(1) Recently, Kocsis *et al* (2011 *Science* **332** 1170) reported the observation of 'average trajectories of single photons' in a two-slit interference experiment. This was possible by using the quantum weak-measurement method, which implies averaging over many events, i.e. in fact, a multi-photon limit of classical linear optics. We (NJP 2013) give a classical-optics interpretation of this experiment and other related problems. Weak measurements of the local momentum of photons made by Kocsis *et al* represent measurements of the Poynting vector in an optical field. We consider both the real and imaginary parts of the local momentum and show that their measurements have been realized in classical optics using small-probe particles. We also examine the appearance of 'anomalous' values of the local momentum: either negative (backflow) or exceeding the wave-number (superluminal propagation).
(2) Momentum and spin are fundamental dynamical properties of quantum particles and fields. In particular, propagating optical waves (photons) carry momentum and longitudinal spin determined by the wave vector and circular polarization, respectively. We show that exactly the opposite can be the case for *evanescent* optical waves. A single evanescent wave possesses a spin component, which is *independent of the polarization* and is *orthogonal* to the wave vector. Furthermore, such a wave carries a momentum component which is determined by the *circular polarization* and is also *orthogonal* to the wave vector. We have found that a single evanescent electromagnetic wave offers a rich and highly non-trivial structure of the local momentum and spin distributions. In sharp contrast to standard photon properties, evanescent waves carry helicity-independent transverse spin and helicity- dependent transverse momentum. Thus, an exceptional evanescent wave structure with *pure* spin transverse momentum offers a unique opportunity for the direct observation of this fundamental field-theory quantity, which was previously considered as 'virtual'. These results add a distinct chapter in the physics of momentum and spin of classical and quantum fields, and offers a variety of non-trivial light-matter interaction effects involving evanescent fields.

**A few selected publications in this topic:**

Y. Bliokh, A.Y. Bekshaev, A.G. Kofman, F. Nori, *Photon trajectories, anomalous velocities and weak measurements: a classical interpretation,* New J. Phys. **15**, 073022 (2013).
K. Y. Bliokh, A. Y. Bekshaev, F. Nori, *Extraordinary momentum and spin in evanescent waves,* Nature Communications **5**, 3300 (2014).

**"Producing correlated photon pairs from the vacuum fluctuations: Dynamical Casimir Effect"**

We proposed (*PRL* 2009) a way to observe the Dynamical Casimir Effect. Then we worked out a very detailed theoretical study of it and proposed an experimentally accessible scheme (*PRA* 2010). Afterwards, we published more theory and the first experimental observation of this stunning effect (*Nature* 479, 376 (2011)). Thus, the method is clear: First, identify a good problem, work it out systematically, and then publish our results in good journals. This 2011 Nature paper of ours was featured everywhere by the press worldwide. It was selected as a *Physics World* top-five Physics breakthrough of the year 2011. According to *Nature*, coverage of our work on *Nature News* was "The most read news story of 2011".

## ５．主な発表論文等

K.Y. Bliokh, A.Y. Bekshaev, F. Nori: "Extraordinary momentum and spin in evanescent waves", Nature Communications 5, 3300 (2014).

B. Peng, et al.: "Loss-induced suppression and revival of lasing" Science 346, 328-332 (2014).

I. Georgescu, S. Ashhab, F. Nori: "Quantum Simulation" Rev. Mod. Phys. 86, 153 (2014).

Z.-L. Xiang, S. Ashhab, J.Q. You, F. Nori: "Hybrid quantum circuits: Superconducting circuits interacting with other quantum systems", Rev. Mod. Phys. 85, 623 (2013).

P.D. Nation, J.R. Johansson, M.P. Blencowe, F. Nori: "Stimulating uncertainty: Amplifying the quantum vacuum with superconducting circuits" Rev. Mod. Phys. 84, 1-24 (2012).

J.Q. You, F. Nori, "Atomic physics and quantum optics using superconducting circuits", Nature 474, 589 (2011)

C.M. Wilson, et al., "Observation of the dynamical Casimir effect in a superconducting circuit", Nature 479, 376 (2011). Physics World top five Breakthroughs of the Year 2011. Also, the top Readers' choice of 2011 on Nature News.

I. Buluta, S. Ashhab, F. Nori, "Natural and artificial atoms for quantum computation", Reports on Progress in Physics 74, 104401 (2011).

According to the Web of Science, during the past decade, 21 (!) of our papers became **top 1% cited papers in all areas of Physics**. Fourteen (14) of these top 1% cited papers were supported by this grant. By any standards, this world-class performance is outstanding.

〔雑誌論文〕（計　150 件）

〔学会発表〕（計　45 件）

〔その他〕URL：http://dml.riken.jp/

受賞リスト(Franco Nori)：

- 2014: Elected Fellow of the Optical Society of America (OSA).
- 2014: Prize for Research in Physics, Matsuo Foundation, Japan.
- 2013: Prize for Science, the Commendation for Science and Technology, by the Minister of Education, Culture, Sports, Science and Technology, Japan.

Additional distinctions:

2014: Elsevier “Most Valued Reviewer of 2014”.
2014: EPL Distinguished Referee
2013: EPL Distinguished Referee
2011: Elected as Outstanding Referee of the American Physical Society (APS).

## ６．研究組織

(1)研究代表者：フランコ　ノリ
(Franco Nori) RIKEN, CEMS, Group Director
研究者番号：50415262

(2)研究分担者　丸山耕司(Maruyama Koji)
RIKEN, ASI, Researcher
研究者番号：00425646

研究分担者　サヘル　アシュハブ
(Sahel Ashhab) RIKEN, CEMS, Researcher
研究者番号：40469903

(3)連携研究者　ランバート　ニール
(Neill Lambert) RIKEN, CEMS, Researcher
研究者番号：80525915

連携研究者　ブリオック　コンスタンティン (Konstantin Bliokh) RIKEN, CEMS, Researcher, 研究者番号：00724840

連携研究者　ヨハンソン　ロバート
(Robert Johansson) RIKEN, iTHES, Researcher, 研究者番号：10596597

連携研究者　ツイ　ウェイ(Wei Cui)
RIKEN, CEMS, Researcher,
研究者番号：30625653

連携研究者　石田　夏子(Natsuko Ishida) RIKEN, CEMS, Researcher
研究者番号：90708520