【Grant-in-Aid for Scientific Research (S)】

Waveguide quantum electrodynamics on superconducting circuits and its applications

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Purpose and Background of the Research

●Outline of the Research

Waveguide quantum electrodynamics (Waveguide QED) derives from circuit QED as a subfield of microwave quantum optics. It focuses on the control and measurement of the quantum state of a propagating microwave mode on a one-dimensional waveguide. We develop novel techniques in waveguide QED and investigate their applications in quantum information processing and quantum sensing.

●Background of the Research

Microwaves, used in cooking and mobile communications, are also electromagnetic waves as light is. In the 19th century, it was understood that electromagnetic waves propagate as waves of electric and magnetic fields even in a vacuum. In the early 20th century, on the other hand, quantum mechanics taught us that the excitations are quantized into discrete levels separated by an energy proportional to the carrier frequency. Coherent waves are described as a superposition of photons. When we use a single-photon detector, we see photons randomly arriving one by one. Such quantum properties of electromagnetic waves are studied in the field of quantum optics, which was developed in parallel with the advancement of laser physics as well as the study of atom–photon interactions. In the 1980s, cavity QED emerges as a new field, in which a photon confined in a cavity strongly couples to an atom inside, enabling the observation of quantum coherent interaction in between.

Moreover, in the 2000s, circuit QED was initiated, where the control and measurement schemes of superconducting qubits and microwave photons in superconducting resonators were dramatically improved. This kicked off the field of microwave quantum optics and the following development of superconducting quantum computers. The research on waveguide QED started around 2010 and has shown rapid progress in the theory and experiments. Controlling and measuring “flying” photons on the waveguide are largely different from those for “confined” photons in a cavity. Thus, new ideas are awaited, and opportunities for new techniques and applications are anticipated.

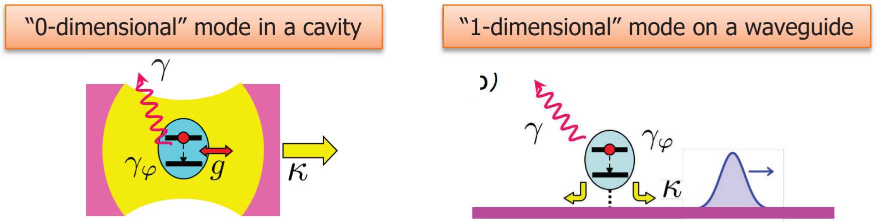

Fig.1 Representative setups of microwave quantum optics. (a) Circuit QED: Interaction between a confined photon in a cavity and a qubit. The coupling strength g, qubit’ energy relaxation rate γ and dephasing rate γ_φ, resonator relaxation rate κ. (b) Waveguide QED: Interaction between a qubit and a photon in a propagating mode on a waveguide. Here, κ represents the energy relaxation rate from the qubit to the waveguide.

●Purpose of the Research

We explore the frontier of waveguide QED by addressing the following questions:

- How can we realize high-fidelity control and measurement of microwave propagating modes on a superconducting 1D waveguide? How can we apply them to quantum information processing?
- How can we send and receive non-classical states in microwave propagating modes by using qubits and parametric amplifiers based on the nonlinearity of Josephson junctions?

●Research topics

① One-dimensional quantum network consisting of all-to-all coupled quantum nodes
② Generation and characterization of temporal-mode quantum entangled states and feed-forward control
③ Development and applications of Josephson traveling-wave parametric amplifiers
④ Applications of microwave single-photon detectors to quantum sensing
⑤ Novel superconducting microwave circuits such as a nonreciprocal device

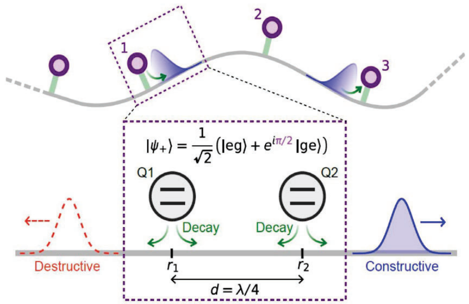

Fig.2 1-dimensional quantum network consisting of all-to-all coupled quantum nodes. Each node consists of two qubits coupled to the waveguide.

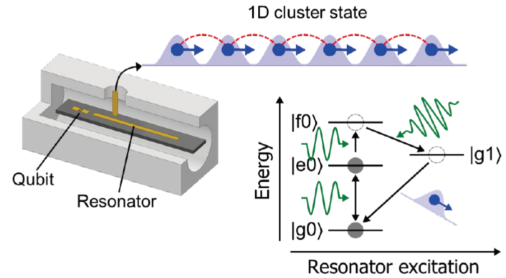

Fig.3 Scheme to generate a microwave photonic cluster state in the time-domain multiplexed wave packet modes using a superconducting qubit in a cavity.

Expected Research Achievements

●Advancement of superconducting waveguide QED and development of new technologies

We develop novel schemes for the control and measurement of a quantum state of a propagating mode on a superconducting waveguide and apply them to quantum information processing and quantum sensing.

●Contribution to quantum technologies

Waveguide QED and microwave quantum optics are critical concepts in the technologies for precise control and measurement of quantum states of electromagnetic fields and apply to various quantum technologies such as quantum computing, communication, and sensing. For superconducting quantum computing, for example, many essential techniques such as the control and readout of the qubits benefit from the knowledge based on microwave quantum optics. Microwave quantum optics remains crucial and will keep contributing to the realization of quantum computing that solves problems relevant to our society

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