Science and Technology Group Annual Report FY2023

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1 Introduction

Quantum computing and related "peripheral" technologies attract significant attention as promising next-generation information processing and sensing applications. Amidst the competitive race for a scalable and versatile quantum computer, superconducting quantum circuits have emerged as the frontrunner. However, the inherent challenges of microwave photon energy and the necessity for ultra-low noise amplification at millikelvin temperatures continue to pose significant obstacles in transferring quantum information between quantum computers.

In response to these challenges, our focus has been on developing spin-based quantum technology devices. This past fiscal year, our team's dedication culminated in significant progress toward realizing a spin-based quantum transducer and a quantum-limited noise amplifier operating at millikelvin temperature based on spin-maser. These devices are not only stepping stones toward next-generation information processing and sensing applications but also platforms for delving into fundamental physics.

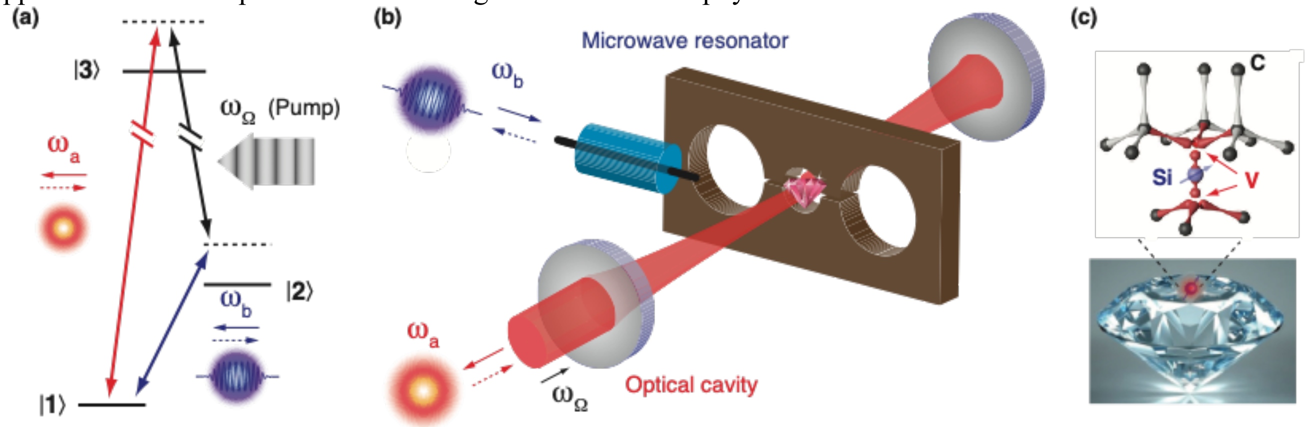

Figure 1: Spin-based quantum transducer. (a) operating principle. The three states ($|1\rangle, |2\rangle$, and $|3\rangle$), the pump tone (ω_Ω), the frequencies of the optical (ω_a) and the microwave photons (ω_b) are shown. It demonstrates the up-conversion of microwave photons and down-conversion of optical photons via a pump laser. (b) Cartoon of the proposed device. A diamond containing impurity spins is coupled with an optical cavity and a microwave resonator. (c) A silicon-vacancy (SiV) center in diamond, the impurity spin used in this project.

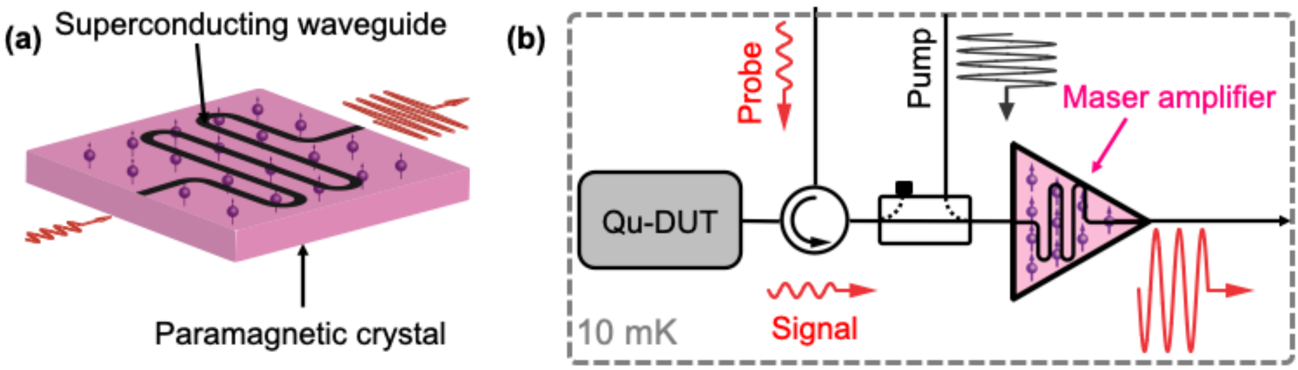

Figure 2: Spin-based quantum-limited amplifier. (a) Cartoon of the proposed amplifier device. A superconducting waveguide is patterned on a paramagnetic crystal. (b) Conceived implementation of the maser amplifier in a quantum information experiment. "Qu-DUT" refers to "quantum device-under-test." The maser amplifier is designed to first amplify weak microwave signals at 10 mK.

2 Activities and Findings

We performed electron spin resonance spectroscopy on impurity spins in diamond crystals at millikelvin temperatures, advanced the design and simulations of the quantum transducer, and further developed the integrated design of the spin-based quantum amplifier.

Our main achievement is encapsulated in the development of a dielectric microwave resonator with large optical apertures that maintain a high internal quality factor—a crucial requirement for spin-based quantum devices. Utilizing rutile-type titanium oxide based dielectric material, we've demonstrated an internal quality factor of approximately $2\text{x}10^4$. This marks a tenfold improvement from our previous loop gap resonator and hints at the potential to exceed a quality factor of one million.

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We have further developed the maser-amplifier device engineered in our previous Proof-Of-Concept project period (Phase I) as shown in Figure **3** (c). The device integrates a broadband coplanar waveguide with a microwave diplexer. The entire assembly is constructed from a sputtered superconducting NbTiN film, shaped using optical lithography and reactive ion etching. The diplexer efficiently merges microwave tones from different frequency ranges.

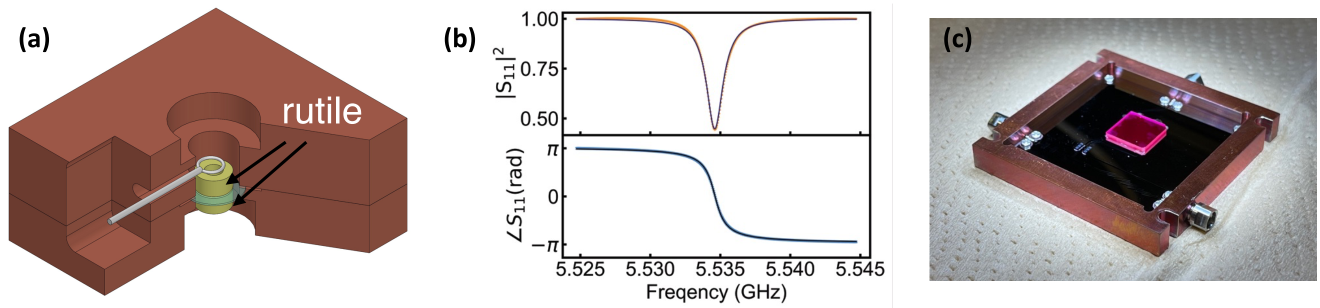

Figure 3: FY2023 activities summary. (a) The dielectric microwave resonator's cutaway drawing showing a hollow-cylindrical dielectric crystal (rutile TiO2, yellow) inside an oxygen-free copper enclosure (brown). (b) A reflection spectrum S11(ω) in amplitude (top) and in phase (bottom) measured at 10 mK. Orange and blue dots represent the experimental data, while the black lines show the fits. (c) A fabricated maser-amplifier device**.**

3 Collaborations

We have initiated partnerships with Orient Microwave Inc., Kyocera, and Kansai-Denshi-Industry Co., Ltd. for the quantum amplifier project, supported by the Proof-of-Concept program at OIST. Additionally, we have embarked on a collaborative project with the University of Tokyo/RIKEN and NICT Kobe for the development of hybrid quantum devices. A JSPS bilateral project was conducted with the group of Prof. Michael Stern at Bar-Ilan University in Israel. Another collaborative project was launched with Dr. Çağlar Girit at CEA-Saclay and CNRS in France, running from March until August 2023, during which Dr. Girit served as a JSPS Invited Fellow at OIST. I have organized several workshops at OIST, including Quantum Information Engineering 2023 (QIE2023) in October, the 49th Quantum Information Technology Workshop (QIT49) in December, and a Quantum Information Technologies Spring School in March 2024.

4 Publications and other output

[1] T. Hamamoto, Amit Bhunia, Rupak Kumar Bhattacharya, Hiroki Takahashi, Yuimaru Kubo, arXiv:2403.08458 (accepted for Applied Physics Letters).

[2] Yuimaru Kubo, "Quantum Techonologies with Hybrid Systems", invite talk at the 5th KMI school (KMI school 2024), Nagoya University, 2024/3/7

[3] 濱元樹,Amit Bhunia, Rupak Bhattacharya, Mathieu Couillard, 高橋優樹, 久保結丸,
"量子トランスデューサーに向けたマイクロ波—光ハイブリッド共振器の極低温動作"
日本物理学会第 78 回年次大会, 東北大学 川内キャンパス, 2023/9/19

[4] 太田守洋, Ching Ping Lee, 高橋優樹, 久保結丸,
"極低温におけるダイヤモンド中の中性電荷 NV 中心の電子スピン共鳴"
日本物理学会第 78 回年次大会, 東北大学 川内キャンパス, 2023/9/19

[5] Morihiro Ohta, Ching-Ping Lee, Yuimaru Kubo, and Hiroki Takahashi(OIST),
"Electron spin resonance of neutral NV centers in diamond at millikelvin temperature", Spins in Lyon Workshop, ENS-Lyon, 2023/12/4

[6] TatsukiHamamoto(OIST),Amit Bhunia (OIST), Rupak Bhattacharya (OIST), Mathieu Couillard (OIST), Hiroki Takahashi (OIST), Yuimaru Kubo (OIST)
"Developing a Hybrid Cavity at Cryogenic Temperatures towards a Quantum Transducer with Color Centers in Diamond", Spins in Lyon Workshop, ENS-Lyon, 2023/12/4

[7] Ching-Ping Lee(OIST), Morihiro Ohta (OIST), Hiroki Takahashi (OIST), Yuimaru Kubo (OIST)
"Charge-photoconversion of the NV centers in diamond and detection by pulse electron spin resonance measurement at low temperatures", Spins in Lyon Workshop, ENS-Lyon, 2023/12/4