ED1-1-INV

Multichannel on-scalp MEG based on high-Tc SQUID magnetometers

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Recent development of high-T_c SQUID magnetoencephalography (MEG) has shown the potential of the technique both as a possible replacement for the traditional low-T_c systems [1-5] and for increased information capacity from the close proximity to the brain [6]. SQUID magnetometers made from single layer high-T_c superconductors usually have an order of magnitude or more higher noise than their multilayer low-T_c counterparts. However, for MEG applications, the simpler cryogenic requirements make it possible to decrease the sensor-to-head distance from 20 mm to approximately 1 mm, retaining the signal-to-noise ratio. Furthermore, higher spatial resolution could be obtained and higher moments of the sources could be resolved from near-field measurements. Here, we report on benchmarking of high-T_c vs. low-T_c MEG and on the development of a multichannel high-T_c MEG system. The system is configured with a densely-packed set of seven 8.6 mm x 9.2 mm high-T_c SQUID magnetometers positioned in a slightly concave hexagonal pattern on a sapphire window connecting thermally to a liquid nitrogen bath. A method of direct feedback injection to the SQUID loops was chosen to minimize crosstalk between the sensors. To improve the field sensitivity, we have developed a new method to produce high-T_c flux transformers for flip-chip arrangements for the next generation MEG system. Finally, we are investigating the possibility to use high-T_c nano-wire based SQUIDs as magnetometers for MEG in future systems.

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Keywords: magnetoencephalography, high-Tc, SQUID, on-scalp

ED1-2-INV

Superconducting Devices Based on Coherent Operation of Josephson Junction Arrays above 77K

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It took a while for Feynman's famous prediction [1] that multiple Josephson junction devices would eventually improve performance of superconducting devices to be confirmed experimentally [2-5]. Such arrays made of low temperature superconductors operate at 4.2K or below and maintaining such low temperatures is both expensive and difficult to handle. This is why high temperature superconductor Josephson junctions operating coherently at 77K are ideal candidates for re-shaping the electronics industry's future. Their advantages over their semiconducting counterparts (higher operating speed, lower power consumption/electronic noise) can be exploited in practice because of their practicality: cooling down to 77K is both cheap and easy to handle. Several promising applications are considerd here. Firstly, when flux coherency is achieved in large SQUID-arrays connected in series magnetic flux sensors or voltage amplifiers can be build having record values for their output voltage and flux noise sensitivities [6] outperforming even single SQUID-based devices operating at 4.2 K. Secondly, when the coherent flux-flow of vortices in parallel asymmetric SQUID-arrays placed in a uniform magnetic field B synchronizes with the collective ac Josephson effect in the array ones can exploit that for the development of B-tunable microwave generators [7]. The coherent flux-flow can be altered by B leading to record values for current amplification [8], highly efficient ratchets with unidirectional vortex motion or integrated nano-magnetic sensors [9].

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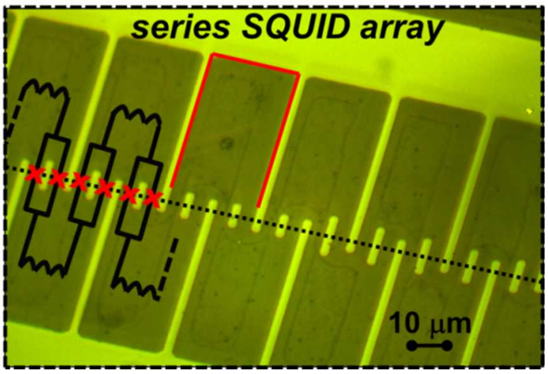

Keywords: Josephson junction arrays

ED1-3

Magnetometer based on transfer and modulation of magnetic flux using HTS coils

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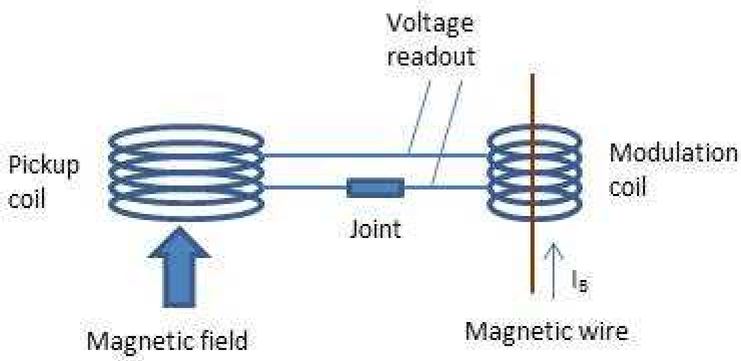
We developed a new type of magnetometer for measuring low-frequency magnetic fields. The principle of operation is based on the transfer and modulation of magnetic flux using HTS coils. Schematic of the magnetometer is shown in Fig. 1. The magnetometer consists of two coils, namely, pickup and modulation coils made of HTS tape. The two coils are connected with very small joint resistance, and form a closed loop. Using the closed loop with very small resistance, we can transfer the magnetic flux collected with the pickup coil to the modulation coil even at low frequencies.

The magnetic flux transferred to the modulation coil is detected using a newly developed readout scheme based on the inductance modulation of the coil. For this purpose, a magnetic wire was inserted into the modulation coil as shown in Fig.1, and a time-varying current I_B was supplied to the wire. In this case, the permeability of the wire is modulated by I_B, and as a result, the inductance of the modulation coil is modulated with time. Utilizing the time-varying inductance, the magnetic flux is converted to an amplitude-modulated voltage across the modulation coil for the measurement. Following the principle of operation, we call the proposed magnetometer induction modulation scheme (IMS) magnetometer.

For a demonstration of this principle of operation, we fabricated a prototype of the magnetometer using HTS tape. The prototype magnetometer can operate at low frequencies down to $f = 0.01$ Hz without diminishing the response. The noise in the magnetic field signal is 40 pT/Hz$^{1/2}$ at 10 Hz. Further work is necessary to improve the performance of the magnetometer.



ED2-1-INV

Micro-fiber coupled superconducting nanowire single-photon detector for near infrared wavelengths

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High-performance superconducting nanowire single-photon detectors (SNSPDs) have enabled numerous experiments and applications especially in modern quantum optics and quantum communication. Two kinds of optical coupling methods for SNSPDs have been developed so far. One is the standard-fiber-coupled SNSPD with the fiber vertically illuminating the meandered nanowires, the other is waveguide-coupled SNSPD with the nanowires fabricated on the surface of the waveguide which guides photons while the fiber is coupled to the waveguide. Here we report a new type of SNSPD coupled with micro-fiber (MF). The photons are guided by an MF and evanescently absorbed by the nanowires of SNSPD when the MF is atop the superconducting NbN nanowires. The room-temperature optical experiments indicated a coupling efficiency of up to 90% with a 1.3-μm-diameter MF for the wavelength of 1550 nm. We were able to demonstrate that the MF-coupled detector achieved system detection efficiency of 50%/20% at the wavelength of 1064/1550 nm with a 2-μm-diameter MF at 2.2K. We expect the MF-coupled high-efficiency SNSPDs may extend to various novel applications such as micro/nano optics.

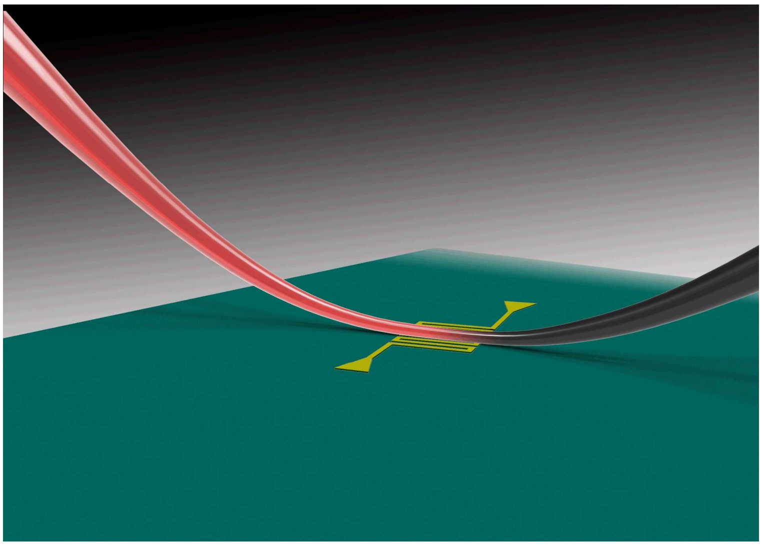

Figure Caption: Schematic of MF-coupled SNSPD.

Keywords: Micro-fiber, superconducting single-photon detector

ED2-2

Microscope imaging with an optical transition edge sensor sensitive to a single photon

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Optical transition edge sensor (TES) detectors which can resolve an energy of a single optical photon have proven desirable in quantum information and biological imaging. We have developed confocal imaging system with a gold-titanium bilayer TES embedded in cavity structure designed to detect photons in a few eV range and lower than this [1]. The TES is formed on a mirror, covered by an anti-reflection coating. The detector has achieved high detection efficiency, nearly 100 % at 1,550 nm (0.8 eV), and an energy resolution of 0.1 eV for 0.8-eV photons. The TES is coupled with the microscope through a fiber which is placed at the confocal plane of a lens and acts as a pinhole. A two-dimensional image can be obtained by scanning a sample. Figure 1 shows an image of blue, yellow and red ink spots scanned by the TES-coupled microscope. The intensity of light source illuminating the sample was set to a level where commercially available CMOS cameras are not usable. The color of each spot was determined based on red-green-blue (RGB) model. We will also show the recent status of development of optical TESes.

[1] K. Niwa et al., Sci. Rep. 7, 45660, (2017).

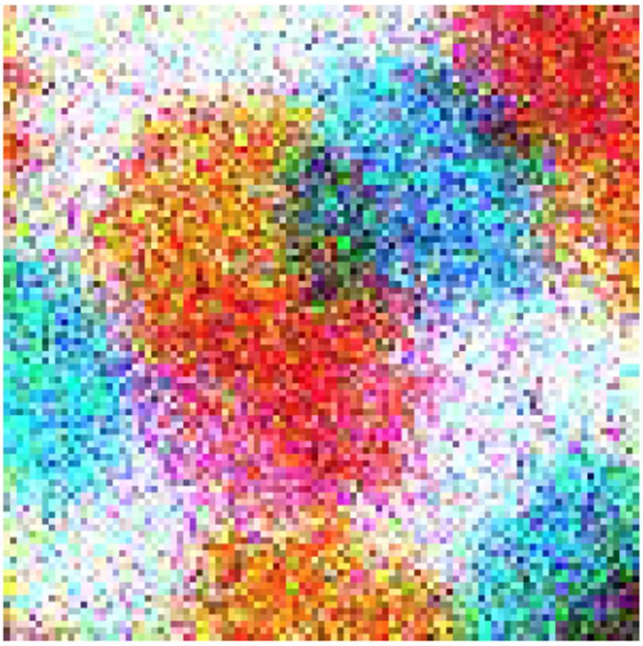

Fig. 1 Blue, yellow and red ink spots illuminated by a faint light source. The gate time was 50 ms for each pixel and the pixel pitch was 2 μm.

Keywords: transition edge sensor, confocal microscopy, two-dimensional imaging

ED2-3

Microwave SQUID Multiplexing for Ti/Au bilayer TES X-ray microcalorimeter

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We are developing a microwave superconducting quantum interference device (SQUID) multiplexer (MW-Mux) aimed to realize more than 10^4 pixels large format superconducting transition edge sensor (TES) X-ray microcalorimeter array, which is larger than that of the Athena X-ray astronomical space mission (i.e., 3840 pixels planned to launch around 2028) in an order of magnitude, for future space missions required large angle and high-resolution spectroscopy such as an Diffuse Intergalactic Oxygen Survey (DIOS). MW-Mux is a multiplexing technique capable of reading out potentially hundreds to thousands of TES pixels in a single coaxial pair because of that three orders of magnitude larger bandwidth than those of conventional multiplexing methods (i.e., TDM, CDM and FDM) with several MHz bandwidths. It consists of a number of superconducting resonators in the GHz range, each employing a unique resonance frequency, terminated by dissipationless rf-SQUID magnetically coupling to a TES pixel. Each SQUID acts as a flux-variable inductor responding to the magnetic flux threading the SQUID loop in a flux-quantum Φ_0 (= 2.07×10^{-15}Wb) cycle. Therefore, a TES signal is read out by monitoring the shift of the resonance frequency depending on the magnetic flux activated by change of current though TES at energy irradiation. For multiplexing, those elements are capacitively coupled to a microwave feedline.

Since the output resistance of Ti/Au TES is generally larger than that of Mo/Cu TES or Mo/Au TES reported from U.S.A., our MW-Mux should have lower current noise than MW-Mux developed in U.S.A. In our condition, the current noises of Ti/Au TES and MW-Mux were respectively ~30 pA/Hz-0.5 and ~100 pA/Hz-0.5. In order to realize the signal to noise ratio higher than one, the coupling between TES and SQUID should be larger than 200 pH, which is about three times as large as our first design.

For this purpose, we are investigating how large the coupling between TES and SQUID can be in our MW-Mux.

In this presentation, we will first describe this result as well as the multiplexing of X-ray TES arrays.

Keywords: Microwave SQUID multiplexer, Transition edge sensors (TES), Microwave resonators

ED2-4

Evaluation of $YBa_2Cu_3O_{7-\delta}$ based microwave kinetic inductance detector array with rewound spiral resonators

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A microwave kinetic inductance detector (MKID), which is one of the superconducting photon detectors, is a promising candidate to realize highly sensitive terahertz imaging due to easy fabrication of large format arrays[1]. However, currently developed MKIDs in other groups utilize low critical-temperature materials for astronomical applications, and they require sizable and expensive cooling systems.

We propose an MKID array using $YBa_2Cu_3O_{7-d}$ (YBCO) thin film that can be easily operated at 77 K. We deposited the YBCO film on a MgO substrate and then patterned a 25-pixels array. The array consists of 25 spiral resonators with the microstrip linewidth of 10 mm as shown in Fig.1(a)[2]. Each pixel is designed to rasonate in the microwave band, and the lengths of the resonators were varied for every 30 mm.

We evaluated the microwave characteristics by measuring one of the scattering matrix elements (S_{21}) using a vector network analyzer. 25 resonant dips were clearly observed at around 5 GHz with intervals of about 15 MHz as shown in Fig.1(b). The average amplitude was 9 dB, and the loaded quality factor (Q_L) was approximately 1300 at 11 K. Each resonant frequency was shifted by 170 MHz by changing the operating temperature from 11 to 50 K. In addition, the arrays with linewidth of 20 and 40 mm were also prepared to compare the detector performance. As for these two resonators, the amplitudes were 12 dB and 18 dB, and the Q_L values were 950 and 600 in average, respectively. As a first step of the optical evaluation, we irradiated a pulsed visible light to the array. The resulting noise equivalent power (NEP) was of the order of 10^{-9} W/sqrt(Hz), and the response time was less than 30 ms at 13 K. We think that the performances of the detector will be improved by optimizing our YBCO film quality as well as the resonator design. The latest results will be given in this presentation.

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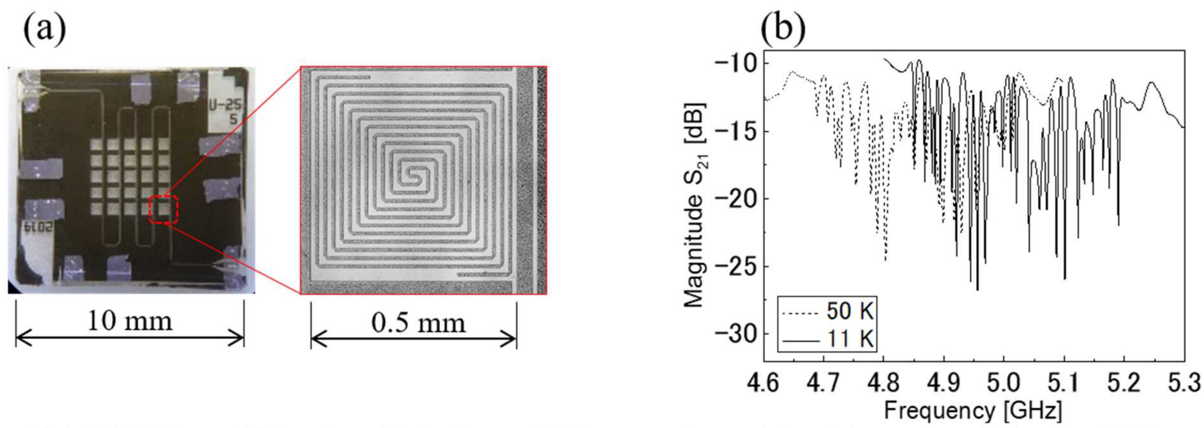

Fig1. (a) MKID array fabricated on a MgO substrate, (b) Microwave characteristics of the array measured at 11 and 50 K.

Keywords: YBCO, MKID, kinetic inductance, microwave resonator

ED3-1-INV

Single-Flux-Quantum Circuits with Nb-doped Si Barriers

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Digital and mixed-signal rapid single-flux-quantum (RSFQ) superconducting circuits are of significant interest to NIST for metrology applications related to advanced computing, on-chip signal processing, waveform synthesis, and voltage standards (both AC and DC). NIST's development of a high-yielding process for fabricating stacked, self-shunted superconductor/normal metal/superconductor Josephson junctions (SNS JJs) with niobium-doped silicon barriers was critical to productizing the 10V DC programmable Josephson voltage standard.[1] By reducing the Nb doping, we leveraged this process to make high-speed, critically-damped, self-shunted superconductor/*insulator*/superconductor (SIS) JJs for RSFQ circuits operating up to 300 GHz.[2] More recently, we have improved our fabrication process and circuit design and modeling capabilities to build digital RSFQ library cells using a 4 metal layer process incorporating planarization of the insulating layers (Fig. 1). These circuits use SIS JJs with a relatively low 4 K critical current density (J_c) of $4.2\text{x}10^7$ A/m^2 (4.2 kA/cm^2); a more advanced process for higher-speed circuits will target SIS junctions with $J_c \sim 10^9$ A/m^2 and sub-micrometer diameters defined by electron-beam lithography, as previously demonstrated.[2] To scale our process to more complex high-speed circuits, we moved the ground plane to the top metal layer (M3) and augmented our process control monitor devices and testing to increase yield and ensure accurate parameterization of our Nb-doped Si JJs for operation at both low and high frequencies. As expected, the barrier shunt conductance and the junction capacitance both increase sharply, as the concentration of Nb in the barrier approaches the insulator-to-metal transition. Optimizing these barrier parameters for our circuits is critical to the goal of extending our quantum-accurate waveform synthesizer to RF frequencies.[3]

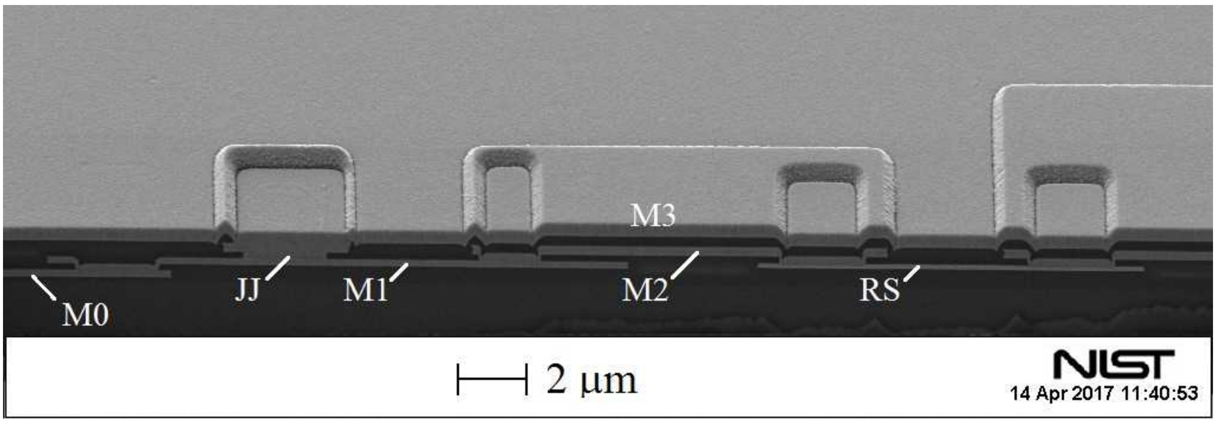

Fig. 1. FIB-SEM cross-sectional image of a wafer from NIST's 4-metal layer RSFQ process. Josephson junction (JJ), resistor (RS) and Nb metal layers M0-M3 are indicated.

1. A.E. Fox et al., IEEE Trans. Appl. Supercond., vol. 25, no. 3, pp. 1101505, June 2015.
2. D. Olaya et al., IEEE Trans. Appl. Supercond., vol. 25, no. 3, pp. 1101505, June 2015.
3. Sam Benz et al., invited talk at ISEC 2017, Sorrento, Italy, June 2017.

Keywords: RSFQ, Josephson junction, metal-insulator transition, superconductive electronics

ED3-2-INV

Coherent caloritronics with Josephson circuits: from heat interferometers to 0-π controllable thermal Josephson junctions

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In this talk I will initially report the first experimental realization of a heat interferometer [1-3]. We investigate heat exchange between two normal metal electrodes kept at different temperatures and tunnel-coupled to each other through a thermal device in the form of a DC-SQUID. Heat transport in the system is found to be phase dependent, in agreement with the original prediction. After this initial demonstration, we have extended the concept of heat interferometry to various other devices, implementing the first quantum `*diffractor'* for thermal flux [4, 5], realizing the first *balanced* Josephson heat modulator [6], and an ultra-efficient low-temperature hybrid `*heat current rectifier*' [7, 8], thermal counterpart of the well-known electric diode [9]. The latter structure offers a remarkable heat rectification ratio up to about 140 which allows its implementation in solid-state thermal nanocircuits and general-purpose electronic applications requiring energy harvesting and isolation at the nanoscale. Finally, I will conclude by showing the realization of a fully superconducting heat modulator based on the first tunable „0-π“ *thermal* Josephson junction [10].

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ED3-3-INV

Niobium-nitride Based Ferromagnetic Josephson Junctions for Superconducting Qubit Application

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Recently, new research field “superconducting spintronics” appeared, and novel physics and device applications in superconductor/ferromagnet (S/F) hybrid structures have been studied actively. The π state of ferromagnetic Josephson junctions (S/F/S junctions), in which the phase difference between the two superconductors is π in the ground state, is attractive as an intrinsic phase shifter for several superconducting devices based on macroscopic quantum effect [1].

In the present work, we have developed the ferromagnetic Josephson junction in order to realize a superconducting flux quantum bit (qubit) with a π junction [2,3]. The qubit with the π junction can be operated without an external magnetic field which is a noise source, and thus good coherence characteristics is expected. Furthermore, zero magnetic field operation provides merits for realizing a highly-integrated system with many qubits. We adopted niobium nitride (NbN) with high superconducting critical temperature of ~16 K as the superconducting material of the junction, which has a relatively smooth surface due to its epitaxial growth on a magnesium oxide substrate. We used copper nickel (CuNi) for the ferromagnetic barrier as a diluted weak ferromagnet, and fabricated the ferromagnetic Josephson junctions based on NbN electrodes with various junction sizes and CuNi thicknesses. We measured and analyzed the dependences of the Josephson critical current on the temperature and CuNi thickness. As a result, we succeeded to develop NbN-based π junctions, and confirmed that our experimental results were explained well by a microscopic theory of the π junctions [4].

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Keywords: Josephson junction, Superconducting qubit, pi junction, Spintronics

ED3-4-INV

Basic Study on AC loss characteristics in frequency band of a few tens of kHz in an HTS pancake-coil for Wireless Power Transmission System

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Tohoku University, Japan[1]

Due to advances in storage battery technology, application of wireless power transmission (WPT) technology to large-capacity devices such as electric tramways has attracted attention. Generally, as the quality factor Q of the transmission and reception coils is higher, the transmission efficiency of the WPT system becomes higher. Therefore, the high Q is obtained by increasing the operating frequency in a typical WPT system using copper coils. However, it is necessary to lower the operating frequency of the large capacity WPT system due to constraints of the switching frequency of the power converter and the capacity of the power supply. Therefore, when copper coils are used for WPT system in a few kHz frequency band, it is difficult to achieve both high capacity and high efficiency.

We are investigating the possibility of large capacity wireless power transmission system with high temperature superconducting (HTS) coils in frequency band of a few tens of kHz. HTS conductor does not have electric resistance. However, when an alternating current flows through an HTS conductor, an AC loss occurs. An equivalent resistance of an HTS coil is obtained by dividing the AC loss of the coil by the square of RMS value of the AC current and the transmission efficiency of the WPT system largely depends on the equivalent resistance of the HTS coil. Fig.1 shows measurement results of the AC loss and the Q of an HTS coil wound 10 turns by an HTS coated conductor with a copper layer. In the copper coil, the Q increases almost in proportion to the frequency. On the other hand, in the superconducting coil, the frequency increases, the Q decreases. This is because the eddy current loss per second in the copper layer increases with the square of the frequency. In the HTS coil, the Q decreases much as the exciting current increases, but the Q is higher than that of the copper coils at 10kHz or less. More experimental results and analyses will be presented in detail.

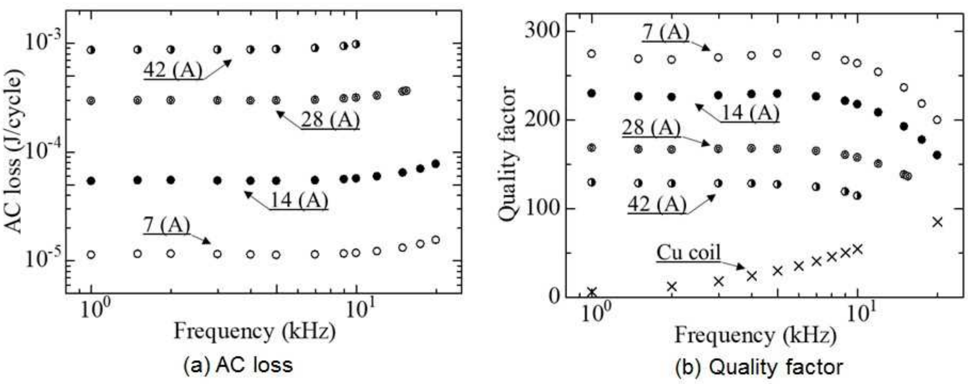

Fig.1 Measurement results of AC losses and quality factor Q in the HTS and Cu coils as a function of frequency.

ED3-5

Generation of Circularly Polarized THz Radiation from $Bi_2Sr_2CaCu_2O_{8+\delta}$ Mesa Structures

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Kyoto University[1]
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In the last decade, continuous wave terahertz sources based on high-T_c superconducting $Bi_2Sr_2CaCu_2O_{8+d}$ (Bi2212) were extensively studied [1]. Mesa-shaped Bi2212 THz sources are compact in size, has a broad tunability range, and extremely monochromic radiation. In many applications, polarization control of the THz radiation is required. However, commonly studied Bi2212 sources in the shape of a rectangular mesa are linearly polarized [2]. Circular polarization (CP) is achievable in Lab environments by using external optical devices such as quarter wave plates. Nevertheless, monolithic generation of CP is highly in demand for compact and portable devices.

In previous reports [3, 4], the CP THz emission from Bi2212 sources has been numerically studied. In the present study, we experimentally show a monolithic Bi2212 based source capable of generating CP THz radiation. The device discussed in this study is in the shape of a cylindrical mesa with two notches, one on each side of its diameter. In a temperature of 30 K, the polarization state, as represented by the axial ratio (AR), was found to be as low as 0.5 dB with a tunability between circular to elliptical polarization (> 3dB). The polarization properties are measured by using a rotating wire-grid polarizer in the emission path between the source and a Si-Bolometer.

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Keywords: Intrinsic Josephson Junctions, Terahertz, Polarization

ED4-1-INV

Development of a commercial superconducting quantum annealing processor

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D-Wave Systems Inc[1]

In January 2017, D-Wave announced general commercial availability and the first system order of its D-Wave 2000Q quantum computer. This system implements an algorithm called quantum annealing, and is based upon a superconducting integrated circuit chip with over 128 thousand Josephson junctions. I will review quantum annealing, some of its potential applications, and discuss some of the unique challenges encountered commercializing a technology based on superconducting circuits.

Keywords: Quantum computing, Quantum annealing, Josephson junction, Superconductor electronics

ED4-2-INV

ASAC: Application Specific Annealing Circuit – A New Approach Towards Designing a Quantum Annealing Superconductor Integrated Circuit

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A new approach towards designing a quantum annealing superconductor integrated circuit, called Application Specific Annealing Circuit, or ASAC in short, is proposed in this presentation. Quantum annealing circuits designed so far, i.e. generations of pioneering superconductor chips from D-Wave Systems among others, have a fixed regular structure, consisting of general-purpose qubits and flexible couplers with a wide range of variable coupling strength to connect qubits to each other. This design is very similar to the structure of FPGA (Field Programmable Gate Arrays), which has become very popular in the CMOS logic market these days, and provides similar benefits such as: 1) reconfigurability to suit as wide users' needs as possible by mapping a wide range of problems onto the common regular structure, 2) fault-tolerance by mapping the same problem in several ways to avoid faulty parts of the chip and to enhance the usability of the system, and so on.

Although these benefits are essential for the commercial systems to gain as wide markets as possible, the fact remains that there is a performance gap between FPGA and ASIC, which provides several opportunities for performance improvement to be investigated. This motivates our new approach ASAC, in which qubits, couplers (strength and topology), and so on, are specialized and optimized to solve a specific optimization problem in the most efficient way. In this presentation, we will discuss the technical opportunities of ASAC, and show our current development effort on ASAC for integer factoring as an example.

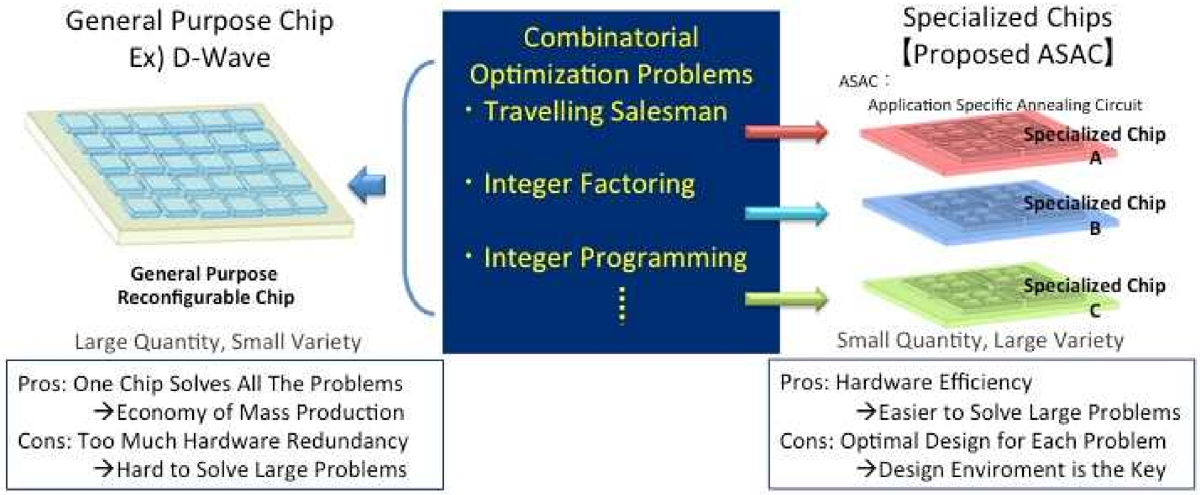

Fig. Concept of ASAC: Application Specific Annealing Circuit

Keywords: Quantum Annealing, Application Specific Annealing Circuit, FPGA, ASIC

ED4-3-INV

Superconducting qubit-oscillator circuit beyond the ultrastrong-coupling regime

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The interaction between an atom and the electromagnetic field inside a cavity has played a crucial role in the historical development of our understanding of light-matter interaction and is a central part of various quantum technologies. The emergence of superconducting qubits has allowed the realization of strong and ultrastrong coupling between artificial atoms and cavities. If the coupling strength g becomes as large as the atomic and cavity frequencies (Δ and ω respectively), the energy eigenstates including the ground state are predicted to be highly entangled. This qualitatively new regime can be called the deep strong-coupling regime.
By inductively coupling a superconducting flux qubit, which has a large magnetic dipole moment due to its macroscopic persistent current states, and an LC oscillator, which has a large zero point fluctuation current, via a Josephson junction coupler with large Josephson inductance as shown in Figure, we have realized deep-strong coupling between the qubit and the oscillator[1]. The spectra obtained in the spectroscopy measurement were well fitted by the Hamiltonian of the quantum Rabi model, which describes a system consisting of a two-level atom and a harmonic oscillator without rotating-wave approximation, and the parameters are obtained to be $g/\omega > 1$ and $g/\Delta >> 1$. We also found that the qubit frequency is suppressed more than 90% from its original value. This can be considered as a huge Lamb shift of the flux qubit due to the deep-strong coupling to the vacuum-fluctuation current of the LC oscillator.

Our results provide a basis for ground-state-based entangled-pair generation and open a new direction of research on strongly correlated light-matter states in circuit quantum electrodynamics.

Reference: [1] F. Yoshihara and T. Fuse et al., Nature Phys. 13, 44 (2017).

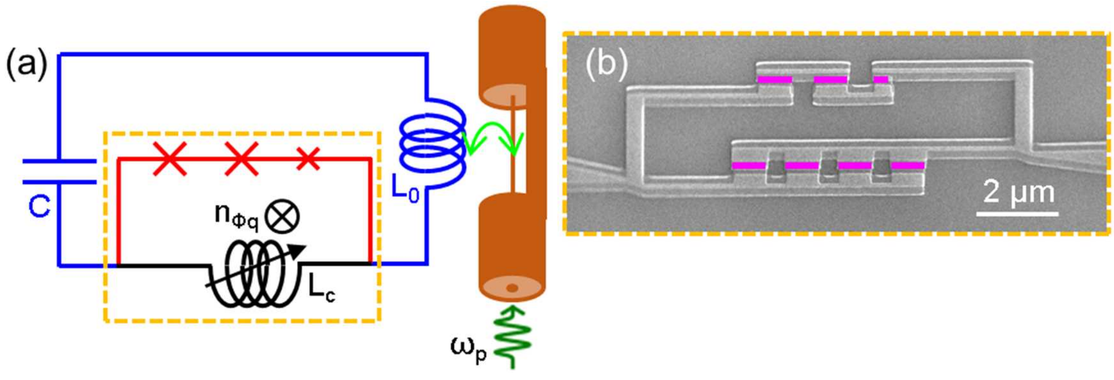

Figure caption: (a) Circuit diagram. A superconducting flux qubit (red and black) and a superconducting LC oscillator (blue and black) are inductively coupled to each other by sharing a tunable inductance (black). (b) Scanning electron microscope image of the qubit including the coupler junctions located at the orange rectangle in (a). Josephson junctions are represented by magenta rectangles. The coupler, consisting of four parallel Josephson junctions, is tunable via the magnetic flux bias through its loop.

Keywords: circuit quantum electrodynamics, superconducting flux qubit, quantum Rabi model

ED4-4-INV

Sensing magnetization oscillation in quantum regime

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Quanta of magnetization oscillation, i.e., magnons, are essential ingredients in spintronics technology. Although their characteristics have been investigated for a long time, the behavior in the quantum regime, where the number of thermal excited magnons is nearly zero, is still unknown. Here we demonstrate ultra-sensitive sensing of magnons using a superconducting qubit. Superconducting "transmon" qubits, which are formed by two electrodes shunted by Josephson junctions, have dipole antennas in their structures and thus they couple to surrounding electromagnetic fields. Owing to their huge dipole moments which are typically 4th-order-magnitude larger than those of atoms, the transmon qubits can detect a change in microwave signal to a single photon level. We exploit such feature for sensing the magnetization oscillation in a magnet. A transmon qubit interacts with an electric microwave field, whereas the magnetization couples to a magnetic microwave field through ferromagnetic resonance. We use a microwave rectangular cavity to induce an effective coupling between them; both the qubit and the magnetization couple with the same microwave field mode but through different components [1]. With an appropriate detuning between the qubit and magnetization oscillation frequencies, the qubit excitation frequency shifts depending on the number of magnons in the magnetization oscillation mode. The qubit resonance peak shift is discretized in the limit where the qubit linewidth is narrower than the shift for a single magnon, so that we can count magnons in the magnetization oscillation mode to a single magnon level. We experimentally show that the coherently excited magnetization oscillation obeys the Poissonian magnon number distribution [2]. Our ultra-sensitive sensing method provides a powerful tool for magnetization oscillation sensing as well as quantum information processing.

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Keywords: Quantum Sensing, Magnon, Superconducting Qubit, Quantum Information Processing

ED4-5-INV

Scanning Nano-SQUID for Nanoscale Thermal Imaging of Dissipation in Quantum System

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Energy dissipation is a fundamental process governing the dynamics of physical systems. In condensed matter physics, in particular, scattering mechanisms, loss of quantum information, or breakdown of topological protection are deeply rooted in the intricate details of how and where the dissipation occurs. More specifically, conversion of electric current into heat involves microscopic processes that operate on nanometer length scales and release minute amounts of power. While central to our understanding of the electrical properties of materials, individual mediators of energy dissipation have so far eluded direct examination.
We recently developed a superconducting quantum interference nano-thermometer device with sub 50 nm diameter that resides at the apex of a sharp pipette and provides scanning cryogenic thermal sensing with four orders of magnitude improved thermal sensitivity of below 1 uK/sqrtHz at 4.2 K [1]. We applied this novel thermal imaging technique to study dissipation processes in hBN encapsulated graphene heterostructures. We reveal local heat released through resonant inelastic electron scattering from individual defects along the edges of graphene that form localized states near the Dirac point. The defects act as switchable phonon emitters providing energy sinks for electrons when brought into resonance with defects' energy levels.

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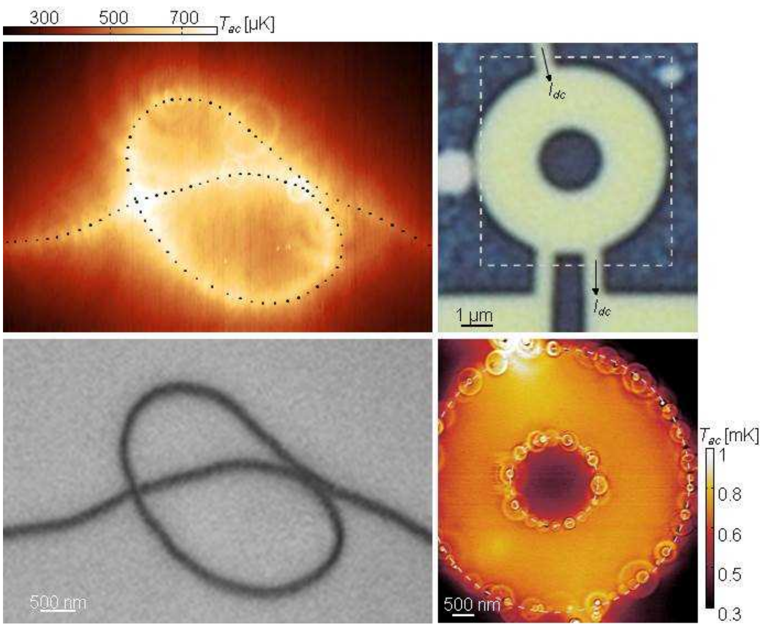

Keywords: Nanoscale thermal microscopy, Scanning nano-SQUID , Graphene

ED5-1-INV

Current Progress in Adiabatic Quantum Flux Parametron

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It is estimated that the power consumption of an exascale supercomputer will exceed 100 MW, if we continue using semiconductor technology. Therefore, superconductor logic is attracting much attention due to its high energy efficiency, and multiple types of superconductor logic are extensively investigated to realize an energy-efficient superconductor supercomputer [1]. We have been investigating adiabatic quantum-flux-parametron (AQFP) [2], which is an adiabatic superconductor logic based on quantum-flux-parametron (QFP) [3]. The switching energy of a single AQFP gate can be arbitrarily reduced via adiabatic switching [4,5], where potential energy evolves gradually between a single-well shape and a double-well shape. In previous studies [6,7], we demonstrated a 10-zJ switching energy in experiments and an even smaller switching energy in numerical calculations. In order to realize a low-power AQFP microprocessor, recently we have designed and demonstrated several data paths and memories, which include an 8-bit carry look-ahead adder [8] and a register file [9], by using customized cell libraries [10] and design tools [11]. In this paper, we will report the detail of these progresses towards an AQFP microprocessor. Moreover, we will also briefly introduce our recent work on an AQFP interface for superconducting single photon detector (SSPD) arrays.

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Keywords: Adiabatic superconductor logic, QFP, microprocessor, detector

ED5-2-INV

Cryogenic signal processing based on superconducting logic circuits for multi-pixel superconducting nanowire single-photon detectors

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Superconducting nanowire single-photon detectors (SSPDs) implemented in compact Gifford-McMahon (GM) cryocooler are used in a wide range of areas, such as quantum information, quantum optics, deep-space optical communication, fluorescence observation, and so on. The system detection efficiency (SDE) of SSPD reaches 90% at the optical wavelength of 1550 nm, which can never achievable in semiconductor photon detectors. However, in many applications, not only high SDE but also total performance including low dark count rate (DCR), high maximum count rate (MCR) and/or low timing jitter are important to determine the system performance. A multi-pixel SSPD is one of promising approaches to realize higher MCR without reducing the SDE and/or larger detection area without reducing the MCR. A multi-pixel SSPD also enables pseudo photon-number resolution also spatial resolution, which will provide a new functionality to SSPD. We have developed multi-pixel SSPDs combined with cryogenic signal processors based on single-flux-quantum (SFQ) circuits. By employing cryogenic signal processing using SFQ circuit, the number of readout cables can be reduced, resulting in reduction of the heat load to the refrigerator [1]. In this talk, we will review our recent progress in multi-pixel SSPDs combined with cryogenic signal processors based on SFQ circuit technology.
This work was partly supported by JSPS KAKENHI Grant No. 26249054. The SFQ circuits were fabricated in the clean room for analog-digital superconductivity (CRAVITY) in National Institute of Advanced Industrial Science and Technology (AIST).

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Keywords: SSPD, SFQ circuit, cryogenic signal processing

ED5-3

A single-flux-quantum based event-driven encoder toward a 1024-pixel single-photon imaging system

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We report on the demonstration of an event-driven encoder using a single-flux-quantum (SFQ) circuit for a 1024-pixel single photon imaging system based on superconducting nanowire single-photon detectors (SSPDs). SSPDs are key elements in various applications such as quantum information systems, diagnostics of semiconductor integrated circuits and fluorescent observation due to their high quantum efficiency, low timing jitter, and so on. A multi-pixel SSPD system has been developed to improve maximum count rate and realize an ultra-high-sensitive imaging system. In a single-photon imaging system using SSPDs, spatial and timing information are important. We already demonstrated a 64-ch SFQ event-driven encoder in a 0.1-W GM cryocooler, which is driven by output signals of an SSPD and encode both spatial and timing information. The 64-ch encoder can handle 64-pixel SSPDs by one-to-one readout method. In order to extend the number of input channels of the system, we designed a 32 x 32-ch SFQ event-driven encoder, which can handle 1024-pixel SSPD based on the 2N readout method. The total number of Josephson Junctions (JJs) of the designed 32 x 32-ch SFQ encoder is 2900. In order to reduce the DC bias currents for the SFQ encoder, we designed the circuits with half critical currents (Ic) of JJs compared to the conventional design. The total required bias currents are 190 mA. The address data, which is spatial information, of SSPDs in each row and column is converted to the number of SFQ pulses. The output data of the encoder are transmitted to room-temperature electronics through the parallel-to-serial converter with the data rate of 100 Mbps. The fabricated 32 x 32-ch SFQ event-driven encoder operated successfully. We report on the detail in the presentation.

Keywords: single flux quantum circuit, SSPD, imaging system

ED5-4

Demonstration of picosecond time resolution of double-oscillator time-to-digital converters using single-flux-quantum circuits

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National Institute of Advanced Industrial Science and Technology[2]

Detection of high-mass molecules, which is difficult to detect with a conventional detector, has been realized by using superconducting detectors [1]. The purpose of this research is to develop an imaging system for intracellular molecules. In the proposed system, imaging is performed based on the time information of the detection signal. To realize the imaging system with high spatial resolution, we focused on a double oscillator type time-to-digital converter (TDC) with single-flux-quantum (SFQ) circuits [2] that can realize high temporal resolution. The TDC consists of two sets of ring oscillators and binary counters, and a coincidence detector (CD), which detects the coincidence of the arrival of two SFQ pulses from two ring oscillators. The time resolution of the TDC is limited by the resolution of the CD. In this study, we have developed a dynamic AND (DAND) gate, which can detect two simultaneous SFQ signal inputs with high accuracy, and realized high time resolution of 2 ps or less. By adjusting the period of both oscillators, we also reduced the jitter accumulated in the oscillators and increased the dynamic range. We conducted 1,000 measurements under the same conditions and demonstrated the picosecond time resolution of the improved TDC. We have estimated that when the TDC is used in the imaging system, the spatial resolution of the order of hundreds of nm is expected.

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Keywords: SFQ circuits, Josephson integrated circuits, TDC

ED6-1-INV

The SQUID and its Applications in the Past 30 Years

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The introduction of the superconducting quantum interference device (SQUID) in the 1960's improved the sensitivity of magnetic sensing by several orders of magnitude. The SQUID enabled unprecedented sensitivity in measurements of electric current, voltage, temperature, susceptibility, and many other physical quantities. It allowed new ways for nondestructive evaluation of critical structures, for example, in airplanes or nuclear plants. Magnetic or conductivity anomalies below the earth's surface could be accurately revealed by measuring magnetic fields from above the ground. The SQUID has been used as detector in NMR, in MRI, bolometers, and accelerometers. One of the most notable applications of the SQUID is biomagnetism, where signals from the heart and brain or other organs are measured. The SQUID has enabled high-quality recordings of cardiac activity, spontaneous brain rhythms as well as evoked neuromagnetic fields, these fields being in the femto- to picotesla range. During the last 30 years, SQUIDs have been made more reliable and more sensitive. Large sensor arrays have been built in particular for biomagnetic applications. SQUID microscopy with tiny sensors have allowed submicron-resolution scanning of susceptibility, characterization of magnetic structures such as magnetic nanoparticles, and testing the quality of microcircuits. The discovery of high-transition-temperature superconductors motivated much work to develop devices that work in liquid-nitrogen temperatures. Several commercial companies now sell SQUID sensors for multiple applications. Here, the development of SQUID sensors and their use during the past 30 years will be described, the emphasis being in neuromagnetic applications.

Keywords: Magnetometer, Magnetoencephalography, Magnetocardiography, Ultra-low-field MRI

ED6-2-INV

Superconducting Detectors: the Past 30 Years and Future Prospects

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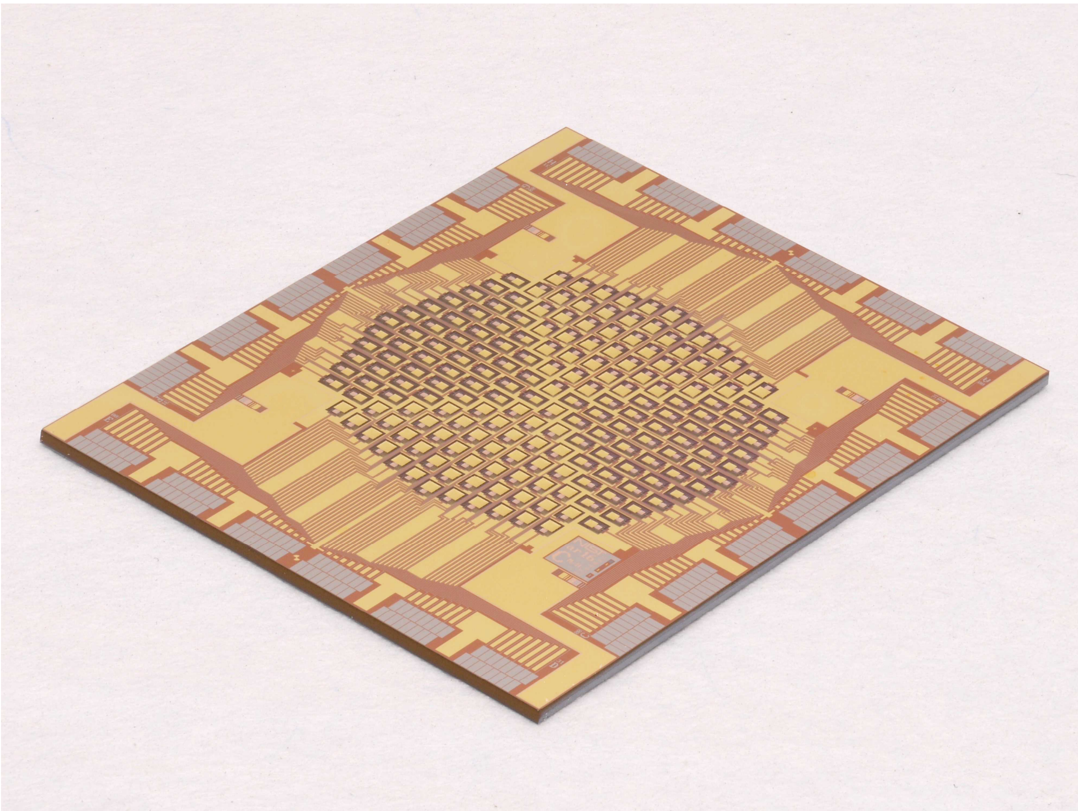
Superconducting detectors are increasingly used to measure photons across the electromagnetic spectrum, as well as for particle detection and searches for exotic particles. In this presentation, we discuss the physical principles that have motivated the study of superconducting detectors, in particular, the potential for sensitivities far surpassing those of more conventional detectors. Then, we review the past 30 years of development in the area of superconducting detectors. Over this period, the use of some technologies, such as transition-edge and kinetic inductance detectors, has steadily grown such that large format arrays (like the one pictured below) are now found in applications as diverse as x-ray materials analysis and millimeter-wave astrophysics. The growing capability of superconducting detectors has produced a virtuous circle wherein the successful entry of superconducting detectors into new application areas has spurred further investment and improvement in the technology. We also discuss the crucial enabling role played by several supporting technologies including convenient cryogenics and superconducting readout circuitry. We then describe the state-of-the-art in superconducting detector technology and some of its many applications. Finally, we discuss potential developments in the years to come.



Keywords: superconducting sensors, transition-edge sensors, microwave kinetic inductance sensors, low temperature sensors

ED6-3-INV

A Thirty History of Superconducting Microwave Devices and Fundamental Studies Thereof

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Thirty years have passed since the discovery of high-temperature superconductors (HTS), and practical applications of HTS equipment and devices are moving into full-swing. From the beginning of their discovery, the use of HTS in microwave devices has been recognized as one of their most practical applications. This is because the microwave surface resistance of HTS is less than 1/1000 of that of pure copper and from early on researchers recognized that high performance of microwave passive devices could be realized by utilizing the characteristics of HTS. In addition, the size of HTS microwave devices is relatively small, and they can be cooled by a small cryocooler. Furthermore, we could establish high-quality HTS thin-film fabrication technology essential for producing high performance microwave devices in a short period of time. In view of the above, I would like to present an overview of the past thirty years of superconducting microwave devices and fundamental studies thereof covering following topics.
(1) HTS film conditions required for highly efficient microwave devices [1]
(2) Superconducting bandpass filters[2,3]
(3) Other prospective superconducting microwave devices[4]

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Keywords: superconducting microwave device, superconducting filter, HTS, NMR superconducting probe

ED6-4-INV

Cryogenic Digital Electronics – Challenges for Practical Use –

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Superconductor-based cryogenic digital electronics has advanced much in the last decade. Single flux quantum (SFQ) circuits, in which an SFQ works as an information carrier, evolves from the rapid single flux quantum (RSFQ) logic circuit into several types of energy-efficient circuits such as the energy-efficient RSFQ circuit (ERSFQ, Hypres), the reciprocal quantum logic circuit (RQL, Northrop Grumman), the adiabatic quantum flux parametron circuit (AQFP, Yokohama Nat'l Univ.). The power consumption of these circuits is 1/10 or less compared to that of the RSFQ circuit with no or small reduction of operating frequencies. Our group has demonstrated an 8-bit-parallel RSFQ arithmetic logic unit (ALU) at 50 GHz by introducing the gate-level pipelining technique proposed by Kyushu University based on the Nb-based integrated circuit (IC) technology of the CRAVITY, AIST. The ALU has shown better performance in both the computing power defined as the number of million instructions per second (MIPS) and the power efficiency (MIPS/W) than the best semiconductor ALU, even if the cooling penalty is considered.

It is often said that difficulty of realization in large capacity cryogenic memories is an obstacle to practical applications of the SFQ ICs. However, nano-cryotrons (nTrons) invented by the MIT group showed a large output voltage up to 1 V. This device opened the way for directly driving a large capacity cryo-CMOS memory or other cryogenic memories including magnetic-Josephson-junction-based memories. Presently, we are struggling to drive a cryo-CMOS memory with an RSFQ decoder through NbN-based nTrons.

We already have a solution to all the obstacles. We believe that superconductor cryogenic digital electronics edges closer to practical use.

Acknowledgment

This work is financially supported by JSPS KAKENHI (16H02340, 26220904, 16H02796).

Keywords: single flux quantum, integrated circuit

ED6-5-INV

Coherent superconducting circuits and quantum information – 30 years' advancements

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In this talk, three decades' progresses in the field of superconducting circuits that exhibit macroscopic quantum coherence, as well as their application to quantum information processing is reviewed.

EDP1-1

Neuro-inspired Quantum Associative Memory Model

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It is widely known that adiabatic Hamiltonian evolution algorithm [1] (including quantum annealing [2]) can solve combinatorial optimization problems. To enhance the versatility of its application, we have investigated the fusion of quantum and neural computing, because neural computing has succeeded to acquire algorithms automatically. As a first step of implementing learning function on quantum computers, we have proposed a neuro-inspired quantum associative memory (NQuAM) model [3] with a quantum neural network (QNN) which is composed of multiple qubits regarded as neurons. The memorization of the NQuAM is realized with a Hamiltonian derived from qubit-qubit interactions converted from neuron-neuron interactions of a conventional neural network. Then the adiabatic Hamiltonian evolution is performed to retrieve memorized patterns. A conventional neural associative memory converges to a certain state corresponding to one of the memorized patterns according to an initial state given as a key input. On the other hand, the NQuAM state is given as a superposition of all memorized patterns and does not converge to a specific state unless some additional treatment is applied. Therefore, we apply an external Hamiltonian H_{fix} to fix the state of some qubits, which imitates the role of a key input for a neural associative memory. Figure 1 shows the average retrieval probabilities $<P_{\mathrm{ret}}>$s of the 4-qubit NQuAM, where A_{fix} denotes an amplitude of H_{fix}. Thus, the effectiveness of H_{fix} is confirmed. The memory capacity M_{cap} of the NQuAM is estimated as 2^{N-1}, where N is the number of qubits. Because M_{cap} of a conventional neural network is order of N, the large memory capacity of the NQuAM would be a big advantage. To receive the profit of the NQuAM model, it is necessary to investigate its hardware implementation. In this report, it will be discussed how to realize the NQuAM hardware with superconducting devices.

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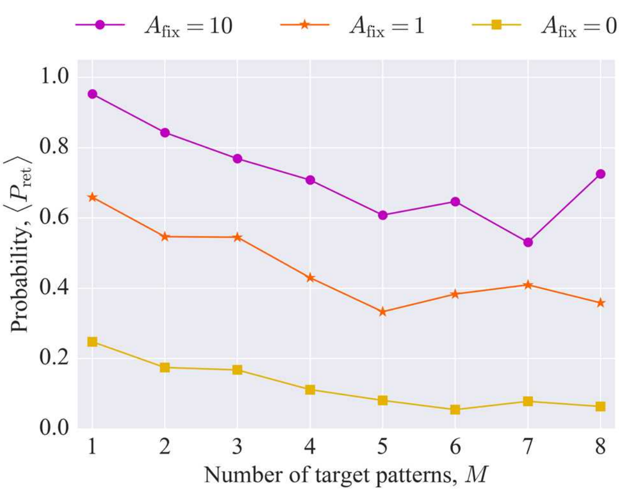

Keywords: quantum computing, associative memory, quantum neural network

EDP1-2

Double-Flux-Quantum Amplifier with a Single-Flux-Biasing Line

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A Double-Flux-Quantum (DFQ) amplifier multiplies its input voltage with quantum accuracy by use of DFQ generation at under-damped junctions [1]. We conducted research on digital-to-analog converters implemented with DFQ amplifiers for metrological applications. Conventional DFQ amplifiers were usually operated with two flux-biasing lines. In this research, we redesigned the circuit layout to realize operation with a single flux-biasing line.
The equivalent circuit of the redesigned basic cell is shown in Fig. (a). Our previous work related to the reduction of flux-biasing lines suggested the new parameter set of a DFQ amplifier [2], although we demonstrated its operation partially. So we refined the equivalent circuit as shown in Fig. (a), where the inductance L_4 was introduced. We designed a new layout of a 20-fold DFQ amplifier and fabricated it using the Nb STP2 of the National Institute of Advanced Industrial Science and Technology.
The measurement was performed in liquid He. The SFQ pulse train was fed by the over bias method, and the input-output characteristics were measured with an oscilloscope (Fig. (b)). When the magnetic flux bias current I_{fb1} was not applied, the maximum input voltage V_{inmax} was 68 V (red), which was about 4.2 times larger than that of 16 V (blue) of V_{inmax} of the previous study [2]. V_{inmax} was enhanced to 120 V with I_{fb1} of 1.00 mA (purple).

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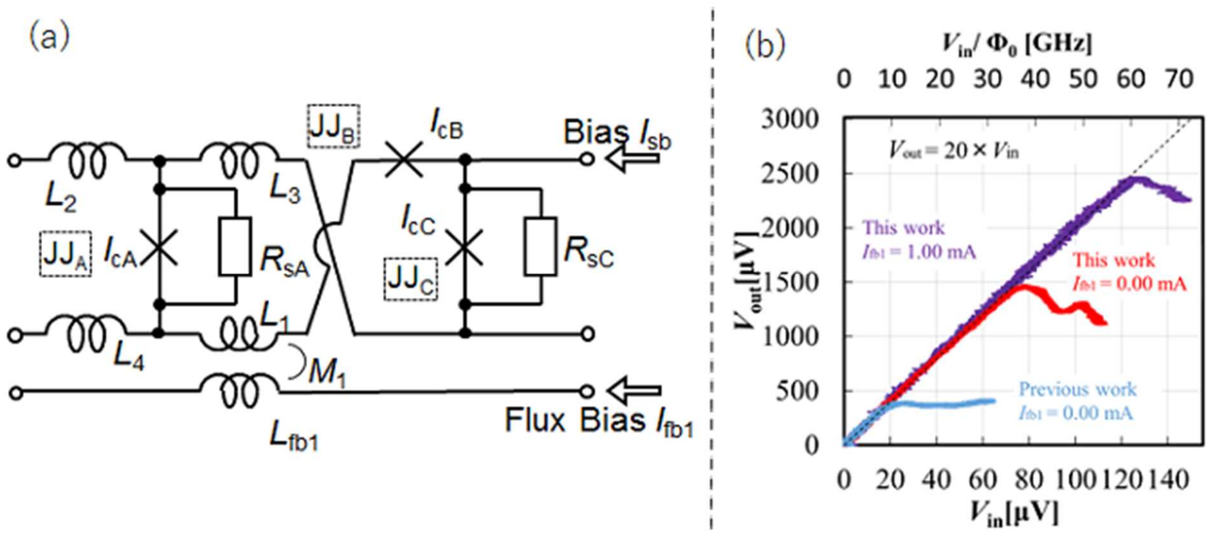

Fig. (a) DFQA of the basic cell; 3 Junctions Loop, (b) Input-Output(*Vin-Vout*) characteristics demonstrating 20-folds voltage multiplication

Keywords: Double-Flux-Quantum Amplifier, Quantum voltage multiplication, Nb integrated circuits
210025

EDP1-3

A random-access-memory cell based on quantum flux parametron with three control lines

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Adiabatic quantum-flux-parametron (AQFP) logic has a potential to become a basic technology to realize an ultra-low-power computing system because of its extremely low bit-energy with three orders of magnitudes lower than that of rapid single-flux-quantum logic [1]. Although large-scale random-access memories (RAMs) are needed for realizing high-performance computing systems, any RAMs compatible with AQFP have not been studied yet. In this study, we have proposed a RAM cell composed of quantum-flux-parametron (QFP) circuits as a component of a large-scale AQFP RAM. The memory cell is composed of a storage QFP gate and a read AQFP gate. The memory cell in our previous study needs three control currents for writing and two control currents for reading, This time, we have proposed a new random access memory cell controlled by three control currents (I_d, I_y, I_x), where I_d corresponds to the input datum, I_y is the column selection current for writing and I_x is the row selection current for both writing and reading. The number of control lines has been decreased by reading memory cells in the same row at the same time and by using common word line for both writing and reading. We have optimized the circuit parameters of the memory cell to increase the bias current margins using the Josephson circuit simulator (JSIM). The evaluated control current margins are larger than +/- 30%. The cell size is estimated to be 50 mm x 40 mm, which can be further decreased by using multi-metal-layer processes. Cell test results will be shown in the presentation.

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Keywords: QFP, AQFP, memory, Josephson integrated circuits

EDP1-4

Proposal of superconducting analog to digital converter using quantum flux parametron

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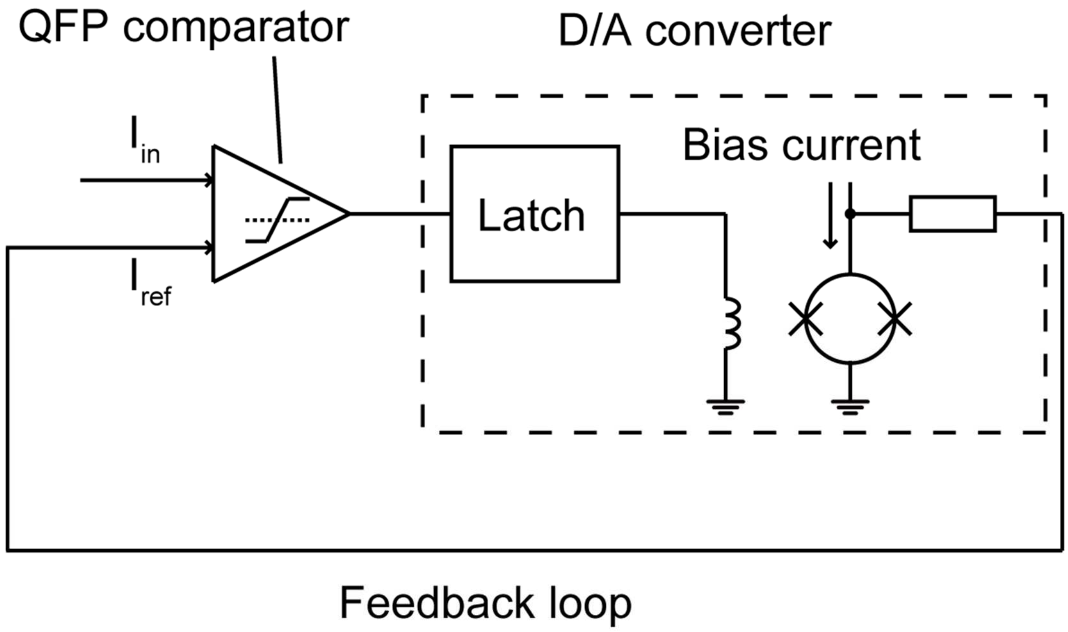
Various superconducting analog to digital converters (ADCs) that have the ultra-high sampling rate have been studied [1]. Because those superconducting ADCs use internal magnetic feedback when one single-flux-quantum (SFQ) signal is output, the input magnetic signal resolution is limited to be one magnetic flux quantum in superconductors. In this study, we propose a superconducting ADC that has better signal resolution than that of ADCs proposed so far by utilizing quantum flux parametron (QFP) [2] as the signal detection circuit. Because magnetic flux resolution of the QFP is less than 1/100 of magnetic flux quantum at the sampling frequency of 1 GHz [3], the input resolution of the ADC can be improved compared to conventional superconducting ADCs. Figure shows a block diagram of the proposed superconducting 1-bit ADC that employs the successive approximation method. By comparing the input signal (I_{in}) and the reference signal (I_{ref}) by the QFP comparator, the input signal is quantized. The reference signal is generated by the digital to analog converter composed of the quantum flux latch (QFL) [4] that stores comparing results output from the QFP comparator. By connecting the circuit shown in the figure in series, the *n*-bit successive approximation ADC can be built. We simulated and confirmed correct operation of the proposed ADC. Performances of the ADCs such as the minimum quantization level and the maximum sampling frequency are investigated on the basis of theoretical analysis and the circuit simulation.



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Keywords: Quantum flux parametron, ADC, comparator, high sensitivity

EDP1-5

Study on Integer-Number Parallel Divider Based on Single Flux Quantum Logic

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Division is one of important arithmetic instructions in the computation systems. Especially, division is frequently used for the scientific application. Among the arithmetic operations, division is one of the most complex calculations in the computation systems. If division is calculated by a general-purpose arithmetic logic unit (ALU), that results in long calculation time. This is thought to be serious problem for single-flux-quantum (SFQ) digital processor [1] that usually employs bit-serial processing.

In this study, we investigated and designed an integer-number SFQ divider based on bit-parallel and bit-slice architectures [2]. Fig. 1 shows a block diagram of the SFQ *n*-bit parallel divider based on a non-restoring division algorithm. We designed the parallel divider using the AIST 10 kA/cm^2 Nb advanced process [3]. Logic simulation results indicate the maximum operating frequency is 77.5 GHz. The bias margin at the target frequency of 50 GHz is 80%–125%. Details of the circuit design and experimental results will be presented at the conference.

Acknowledgement

In this work, the CONNECT ADP cell library and tools were used in this study. The circuits were fabricated in the clean room for analog-digital superconductivity (CRAVITY) at AIST with the advanced process 2 (ADP2).

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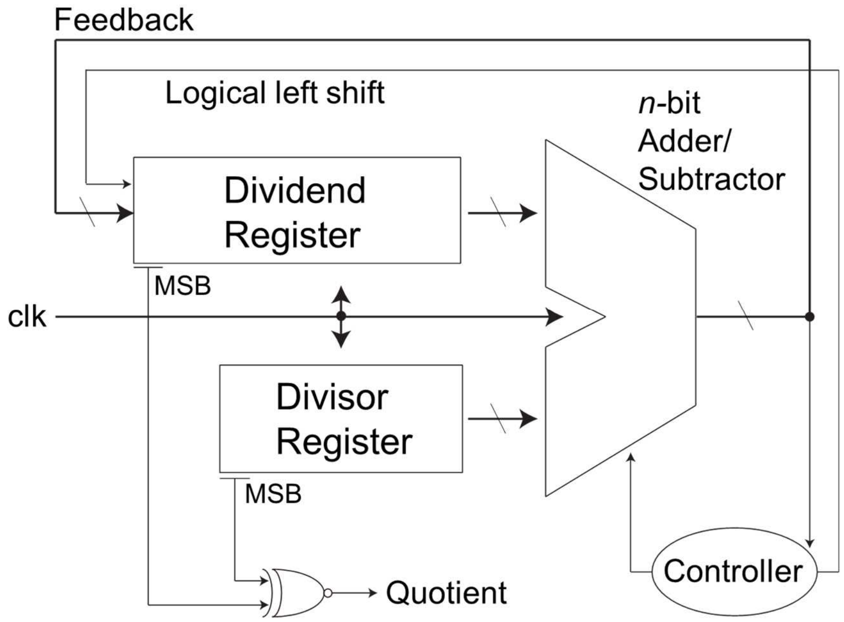

Keywords: Single flux quantum logic, Superconducting integrated circuits, Divider

EDP1-6

Design of an arithmetic logic unit and a data shifter for adiabatic quantum-flux-parametron-based microprocessor

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Adiabatic quantum-flux-parametron (AQFP) logic is an emerging technology in superconducting electronics that shows promise towards building extremely energy efficient computing systems with bit energies approaching $100k_BT$ and has already demonstrated circuits consisting of more than 1000 Josephson junctions. In the effort of building an AQFP-based microprocessor, we have designed two key datapath units using a 4-phase AQFP logic library: a 4-bit arithmetic logic unit (ALU), and a 4-bit data shifter.
The ALU is based-on the Kogge-Stone prefix-adder structure and supports arithmetic addition and subtraction operations, as well as logical operations, namely: AND, OR, XOR and XNOR. It was designed based on a semi-custom approach where sub-blocks were designed by hand using the logic cell library. Sub-blocks were then arranged together into logical rows. The 4-phase bias connections consisting of 2 ac lines and 1 dc line were automatically generated from our AQFP electronic design automation (EDA) toolchain. The logical wiring between gates were completed in a similar way.
The data shifter has been completely synthesized using our EDA toolchain based on the open-source 'yosys' logic synthesis tool with an AQFP cell mapping file. This combinational data shifter supports left/right logical shift, and arithmetic right shift operations.
Both datapath units have been designed using the AIST 10 kA/cm^2 high-speed standard process (HSTP) and have been simulated using the clock-skew aware SystemVerilog models included in our cell library. It is expected that these units can operate at 5 GHz, the clock rate target of our AQFP microprocessor. The ALU and data shifter consists of 1058 and 498 Josephson junctions, and have a latency of 5 cycles (20 phases), and 2.5 cycles (10 phases) respectively.

Acknowledgment
This work was supported by a Grant-in-Aid for Scientific Research (S) (No. 26220904) from the Japan Society for the Promotion of Science (JSPS). This work is also supported by VLSI Design and Education Center (VDEC), the University of Tokyo in collaboration with Cadence Design Systems, Inc.

EDP1-7

Development of the Large-scale Superconducting Nanowire Single-photon Detector Imaging Array

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Development of a large-scale Superconducting nanowire single-photon detector (SSPD or SNSPD) imaging system has recently attracted attention. Since the SSPD has excellent characteristics such as high system detection efficiency, low dark count rate, and superior timing resolution, it has been applied in various research fields. In addition to these excellent characteristics, the SSPD imaging system has the feature that it is possible to identify photon detection positions with high detection timing resolution. This unique feature has the potentiality of application to a wide range of fields such as biological imaging, laser imaging detection and ranging (LIDAR), spectroscopic measurement, quantum imaging and so on.
A major issue in the development of the large-scale SSPD imaging system is heat inflow through enormous readout lines. To overcome this heat inflow problem, we are developing the large-scale SSPD imaging system with two readout multiplexing technologies. The first one is a new multiplexed readout architecture for a SSPD imaging array which recently demonstrated by the NIST group [1]. This architecture remarkably reduces the number of wiring lines required for the N x N array to 2N from N^2. The second technology is readout multiplexing using cryogenic signal processors based on single-flux-quantum (SFQ) circuits. We already demonstrated a 64-channel event-driven serial encoder composed of the SFQ circuit, which for a 64-pixel SSPD imaging array with conventional one-to-one readout architecture. By improving this encoder for the new readout architecture, it becomes possible to readout information of detection position and detection time from the 32 x 32 = 1024-pixel imaging array via only two serial lines.
In the presentation, we report fabrication of a 1024-pixel SSPD imaging array with above new readout architecture. We also report the results of evaluating its superconducting and photo responsive properties.

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Keywords: Single-photon detector, Nanowire, Imaging array, SSPD

EDP1-8

Study on Multipoint Guided Wave Measurement Technique on Pipes using HTS-SQUID NDI System

*Yoshimi Hatsukade[1], Natsuki Masutani[1], Yuki Azuma[1], Kazuya Sato[1], Tarou Yoshida[1]

Kindai University[1]

This paper describes study on multipoint ultrasonic guided wave measurement technique on pipes using HTS-SQUID nondestructive inspection (NDI) technique. The HTS-SQUID NDI system based on T (0, 1) mode ultrasonic guided wave utilizing magnetostrictive effects and a HTS-SQUID gradiometer was used. To generate the guided waves using the magnetostrictive effects, thin nickel board were magnetized using a solenoid coil. By changing a current amplitude supplied to the coil, magnetization fields to the nickel board inside the coil were changed. Distribution of leakage fields around the magnetized nickel boards were measured using a Hall sensor. We found that the leakage field at 12 mT were more uniform than that at 6 mT, which affects the performance of the HTS-SQUID gradiometer, which is set near the magnetized nickel board to measure magnetic signals from the nickel board based on the magnetostrictive effects. The maximum amplitude of the magnetized field from the nickels board magnetized at different magnetization fields did not differ significantly. Finally, the nickel boards magnetized at 12 mT was firmly adhered around circumferences of a sample aluminum pipe, and multipoint guided wave measurement around the pipe was carried out using the NDI system. While supplying a burst sine wave current of one cycle with 1 A_{pp} at 60 kHz into a field coil wound around the nickel board, distribution of the magnetic signals due to generated guided waves on the pipes around the circumference of the pipe was successfully measured.

Keywords: HTS-SQUID gradiometer, guided wave, pipe, multipoint measurement

EDP1-9

Ultra Low Field SQUID-MRI using Non-Resonant Cu Wound Flux Transformer

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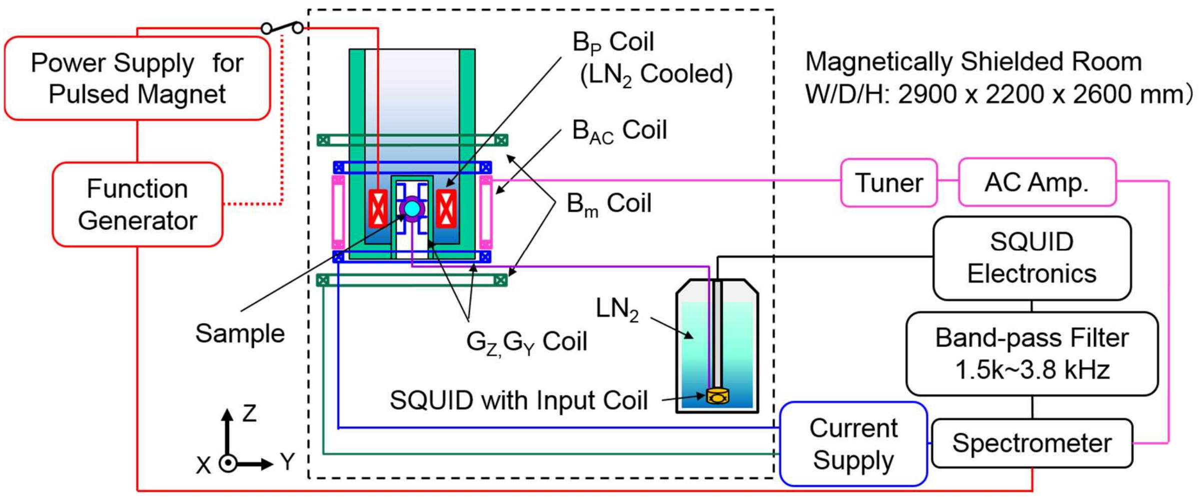
We are developing an Ultra Low Field (ULF) Magnetic Resonance Imaging (MRI) system with high-temperature superconductor superconducting quantum interference device (HTS-SQUID) for the purpose of food contaminant inspection. The new system using the ULF SQUID-MRI technique has the potential to detect not only a metallic but non-metallic contaminants. Since our previous ULF SQUID-MRI system for food inspection used a resonant circuit to detect a magnetic field, which was tuned at Larmor frequency. However, a Q value of the resonant circuit corresponding to the sensitivity became poor with decrease of the frequency of MR signals. In order to increase the Q value, it is necessary to elongate the signal acquisition time, which corresponds to a reciprocal number of the bandwidth. Therefore, it is difficult to measure the MR signal of food with short relaxation time, such as fat, because of the longer acquisition time.
In this paper, we will describe a ULF SQUID-MRI system using a non-resonant Cu wound flux transformer to measure fat of which relaxation time is shorter. Fig.1 shows a schematic of the ULF SQUID-MRI system. The main system consists of the following units: An HTS dc-SQUID with flux transformer, a Helmholtz type measurement field (B_m) coil, an AC pulse (B_{AC}) coil, two sets of gradient field coils (G_x, G_z), a polarizing field (B_P) coil and an NMR spectrometer (Kea[2], *Magritek*, New Zealand). The flux transformer consists of a pickup coil at room temperature and a flip chip type input coil integrated with the SQUID.
The MR image of food contaminant sample will be discussed on the day.



Keywords: HTS-SQUID, ULF-MRI, Food inspection, Flux Transformer

EDP1-10

Constructing a Vector Scanning SQUID System

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Superconducting quantum interference device (SQUID) is a fundamental sensor in constructing an ultrasensitive magnetic measurement equipment. In many preceding cases, it is supposed to be impossible to build such a highly sensitive instrument except for SQUID. Therefore, the SQUID devices are employed in various fields such as magnetics, electronics, biology, spintronics, security analysis, agriculture, information technology, communication, material science, and physics [1]–[3]. However, a typical scanning SQUID microscope has a single pick-up coil and a single channel SQUID readout circuit to obtain the distribution of local magnetic field component only perpendicular to the sample surface along the Z direction. Recently, we started to develop a scanning SQUID vector microscope equipped with a vector pickup coil (Fig. 1), which intends to achieve high sensitivity in the magnetic field and high spatial resolution in vector field mapping [4], [5]. We placed the positions of X, Y and Z coils to keep the same heights to sample and the distance of center coils to each other in integer of scanning step to make a convenience in synthesizing a vector magnetic field (Fig.1(b)). The new sensors have improved the sensitivity by utilizing multiple windings of the pick-up coil with the aid of multi-layer fabrication process of the superconductive foundry CRAVITY of AIST. Scanning vector SQUID microscopy is under construction by using a 3-channel SQUID readout circuit (Magnicon Inc.), an 3-channel XYZ piezo-driven scanner (Attocube Inc.), and a Gifford-McMahon cryocooler (Sumitomo Inc.). We confirmed that the voltage outputs from the SQUID readout circuit are in good agreement with the profile of the output (V-F) characteristics of the SQUID sensor. The first images of a vortex in a $Mo_{80}Ge_{20}$ thin film were obtained successfully by using our own SQUID sensor in our existing SQUID microscope.

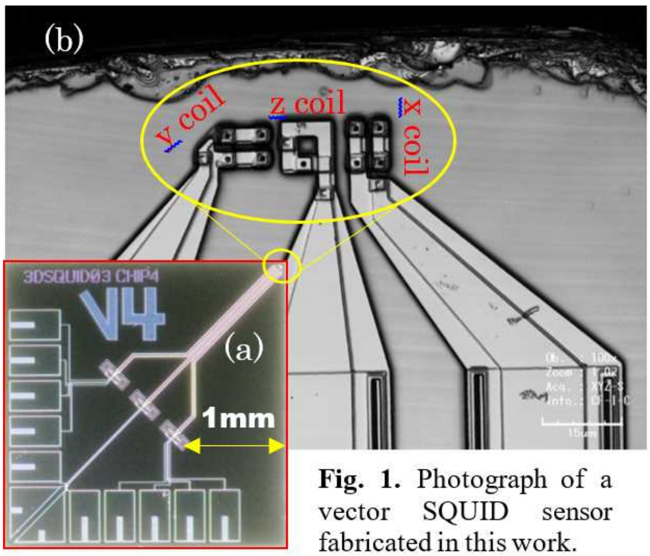

Fig. 1. Photograph of a vector SQUID sensor fabricated in this work.

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Keywords: SQUID microscopy, Vector sensor, Scanning microscope, , 3D sensor

EDP1-11

Precision measurements of transuranium elements using superconducting transition edge sensor

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Nondestructive analysis using gamma-ray and x-ray emitted from radioactive elements is used in a various field such as nuclear transmutation and nuclear activation analysis. In this field, scintillation detectors or high-purity Germanium detectors are used for measuring gamma-ray or x-ray but they are difficult to identify or detect nuclides since the energies of photons emitted by transuranium elements such as Plutonium and Americium are close to each other or gamma-ray or x-ray emitted by nuclides are covered with Compton scattering.
To solve this problem, we focused on the superconducting transition edge sensor (TES) which is an exquisitely sensitive device exploiting the abrupt change in resistance at the onset of the superconducting transition and selectable gamma-ray or x-ray absorber made by high Z material. Therefore, in order to demonstrate the precision measurement of nuclear material samples using a TES microcalorimeter, we have designed and fabricated a gamma-ray TES spectrometer for nuclear material analysis which is Ir/Au-TES and coupled to a tin radiation absorber by using a gold bump post.
In this presentation, we will report the results of irradiated and non-irradiated Np samples by using TES microcalorimeter and we consider that gamma-ray spectrometer using a TES microcalorimeter can be applied to the advanced non-destructed inspection of the nuclide material.

Keywords: superconducting transition edge sensor, Neptunium samples

EDP1-12

Study on Lumped Element Kinetic Inductance Detectors for Light Dark Matter Searches Using Liquid Helium

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We have developed the superconducting detector LEKID (Lumped Element Kinetic Inductance Detectors) for a dark matter search using liquid helium. It is supposed that the dark matter consists of weakly interacting massive particles (WIMPs). Direct searches for the WIMPs have been conducted using Xe, Ge, Si and NaI as targets. Those experiments have sensitivities for WIMP mass down to about 10 GeV/c^2. In 2013, W. Guo and D. N. McKinsey have proposed to use liquid helium as a target to obtain a sensitivity beyond 10 GeV/c^2 in WIMP mass. Helium may have sensitivity to the light WIMP mass less than 10 GeV/c^2, as it is a light element. Recoiled helium atoms produce scintillation light photons with the wavelength of 80 nm (16 eV in energy). Those photons are detected with the superconducting detector LEKID. The LEKIDs offer us a frequency domain multiplexing readout that reduces the number of readout cables, decreasing the heat load from the outside.

The superconducting detectors are fabricated with photolithographic techniques in clean rooms, CRAVITY at AIST and one at KEK. We use Nb or NbN for superconducting materials. The sensitivity of LEKIDs can be estimated by the phase responsivity. We measured temperature dependency of performance of LEKIDs to calculate the phase responsivity. And we measured response of LEKIDs by the visible lights. We report on the current status of the development of LEKIDs that satisfy our requirements.

Keywords: Kinetic Inductance Detectors, Dark matter

EDP1-13

Flip-chip bonding technology for high performance STJ array detector using superconducting bumps

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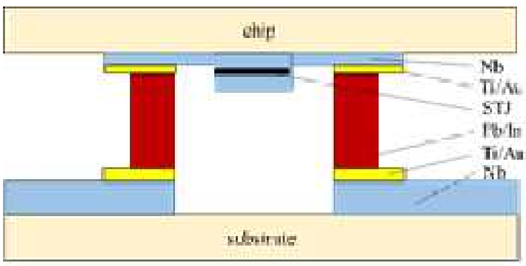
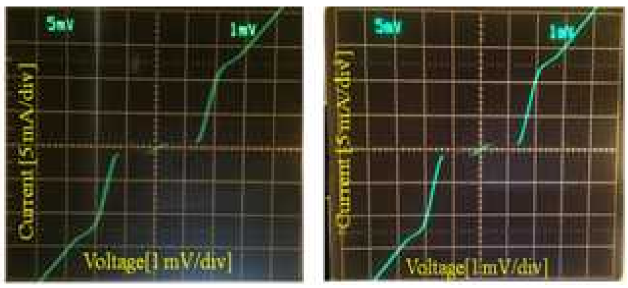
Superconducting tunnel junction (STJ) is one of the candidates as a next generation photon detector because of high energy resolution and wide bandwidth. In order to obtain a two-dimensional image of detected photons, it is necessary to array a large number of STJs on a chip. The integration density of STJs is limited by the wiring area when the STJ-array is enlarged. To solve this problem, we have proposed an "embedded STJ" (e-STJ) with a three-dimensional packaging structure [1].

In this research, we focus on flip-chip bonding (FCB) connection as a three-dimensional mounting method. To obtain high quality detected signal transmission superconducting Pb / In alloy bumps are introduced in the three-dimensional packaging structure. And we have been evaluated the FCB conditions and the electrical characteristics of the bumps.

Fig. 1 shows the schematiccross-sectional view of the sample used in this work. The STJ of upper chip is FCB connected by the Pb / In alloy bumps made on the substrate. The electrical characteristics of the STJ were measured at 4.2K through the superconducting bumps before and after the FCB as shown in Fig.2. The superconducting FCB connection is successfully demonstrated in the three-dimensional packaging structure. The details will be presented.





Keywords: superconducting tunnel junctions, flip-chip bonding, bump

EDP1-14

Development and evaluation of Multi-Layer Superconducting detectors for the CMB polarization observation

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The Big Bang cosmology is a prevailing theory to describe the early universe. It also has outstanding problems such as the flatness problem, the horizon problem and the magnetic monopole problem. The cosmic inflation, exponential expansion of the space, gives an initial condition of the Big Bang to resolve these problems. The inflation theory predicts the existence of primordial gravitational waves(PGWs). The PGWs produce specific polarization patterns (B-modes) on the Cosmic Microwave Background(CMB). B-modes are the direct evidence of inflation [1].
GroundBIRD aims to search for B-modes from the ground. It employs a large-scale array detector of Kinetic Inductance Detectors(KIDs) [2]. The observing frequencies are 145 GHz for the CMB observation as well as 220 GHz for dust foreground subtraction. The sensitivity of the single KIDs required to be the photon noise limited level under the operation temperature of 250 mK and the loading from the sky of Canary Islands.
We investigated the performance of KIDs which employed multilayer of titanium and titanium nitride (TiN). TiN KIDs have a higher responsivity compared to Al KIDs. The critical temperature T_c of TiN/Ti multilayer can be precisely controlled from 1 K to 4 K with excellent uniformity in 3-inch wafer [3]. From BCS theory, the relation between superconducting energy gap and T_c is described to be $\Delta=3.52k_BT_c/2$. Strictly speaking, the relation depends on the material of superconductor. We investigated it in case of TiN/Ti multilayer. We also optimized the T_c by the tuning to the thickness of titanium for the environment of scientific observations. We fabricated 14 TiN/Ti KIDs (T_c =1.72 K) as shown in Fig. 1. The range of resonance frequencies of the KIDs is 3.45 GHz to 3.55 GHz. We measured optical response of these KIDs. The detail results will be presented.

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Keywords: Microwave Kinetic Inductance Detectors, Titanium nitride, Cosmic Microwave Background

EDP2-1

Neutron signal features of Nb-based kinetic inductance detector with ^{10}B convertor

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Our kinetic inductance neutron detector is made of a 40-nm-thick Nb meanderline and a ^{10}B conversion layer with the effective area of 15×15 mm^2 on a single Si chip (22 x 22 mm^2), and is biased by a small DC current I_b at a temperature below T_c. A meanderline of the kinetic inductance detector exhibits a transient change occurs in the kinetic inductance $\Delta L_K = m_s \Delta l / n_s q2S$ of a mesoscopic portion (possible hot spot), where m_s is the effective mass of a Cooper pair, q_s is the effective electric charge, n_s is the Cooper pair density, Δl is the length of the hot spot, and S is the cross-sectional area of the Nb wire. We expect that the voltage V is proportional to a product of the bias current I_b and a time derivative of the kinetic inductance dΔL_K/dt, and a pair of signals propagate along the Nb stripline as an electromagnetic wave at a certain fraction of the light velocity c toward electrodes. We conducted the neutron irradiation experiment at J-PARC. The nuclear reaction $^{10}B(n, {}^4He)^7Li$ releases a ^4He particle of 1.47 MeV and a ^7Li particle of 0.88 MeV, and the energy of each projectile is used to create a hot spot on the Nb nanowire of the detector. It remains to be answered why the signal voltage shows such a continuum in the histogram of the signal height even if the incident energy of the light ion is apparently monochromatic. We also investigated the distribution of the width of the signal pulse. The height and width of the signal has a clear correlation, which might be is the key of understanding the operating principle of our detector. We consider that the origin of the signal distribution is due to the positional dependence of the light ion bombardment with respect to the meandering Nb nanowire.
This work is supported by Grant-in-Aid for Scientific Research (S) No. 23226019, Grant-in-Aid (A) No.16H02450 from JSPS. The devices were fabricated in the clean room for analog-digital superconductivity (CRAVITY). This work is partially benefitted by the use of (VDEC, the University of Tokyo with the collaboration with Cadence Corporation. This work is supported of MLD program (Proposal No. 2015A0129, No. 2015P0301).

Keywords: Kinetic inductance detector , Operation principle, Neutron , Signal profile

EDP2-2

Electrodynamic Theory for the Operation Principle of Superconducting Delay-line Kinetic Inductance Detector

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Generation and propagation of voltage signals in a superconducting delay-line inductance detector, which has been developed for a high-performance radiation detector, is theoretically investigated in terms of superconducting electrodynamics. The detector consists of a meandering superconducting nanowire deposited on a substrate composed of a stack of insulating and superconducting layers. It is shown that this system can be regarded as a superconducting waveguide. We derive a dynamical equation for the superconducting phase difference between the superconducting nanowire and the substrate superconducting layer. This equation predicts the generation of a pair of voltage pulses with opposite polarities when a transient hot spot appears inside the current-biased nanowire. The pair of voltage pulses splits into two single pulses propagating in the opposite directions to each other. The velocity of the voltage pulses along the delay-line is well fitted by our theory.

Keywords: kinetic inductance detector, supercondcuting nanowire, supercondcuting theory

EDP2-3

Signal propagation in delay-line kinetic inductance detector under DC bias current

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We developed a high resolution imaging system by using a current biased kinetic inductance detector (CB-KID) operating in a delay-line mode. It consists of stacking layers of a superconducting Nb ground plane, SiO_2 insulator, and a two set of superconducting Nb meanderlines. When some amount of energy is deposited to the superconducting wire of the meanderline, it produces a hot spot in a tiny segment of the wire, where Cooper pairs are suppressed locally, and induces a temporal change of the kinetic inductance there. If a DC-bias current flows along the meanderline, the transient change in the kinetic inductance excites voltage pulses, which propagate toward both ends of the Nb stripline with opposite polarities. We observe the arrival signals by a digital oscilloscope to store the wave forms. We use the arrival timestamps to identify the hot-spot position of the wire by knowing a time difference in arrival timestamps and the propagation velocity. This is the method how we image the distribution of mesoscopic excitations in both X and Y detectors by irradiation of pulsed neutrons. Therefore, it is important to investigate the propagation velocity before conducting imaging experiments. We applied a test pulse from one end of meander, and the transmitted signal was measured at another end to know the velocity. The basic equation for signal propagation has been derived by Koyama *et al.* by using the Maxwell-London theory on a superconducting waveguide of nanowire - SiO_2 – ground plane (S-I-S) structure. In the theory, the electromagnetic wave is treated as a Swihart pulse. As shown in Fig. 1, we successfully fit the propagation velocity as a function of temperature by using the equation shown in the figure. Since the superfluid density decreases as the temperature increases, the velocity comes from a change in the kinetic inductance. We plan to investigate the velocity as a function of DC bias current, too. The systematic comparison between theory and experiment would be interesting.

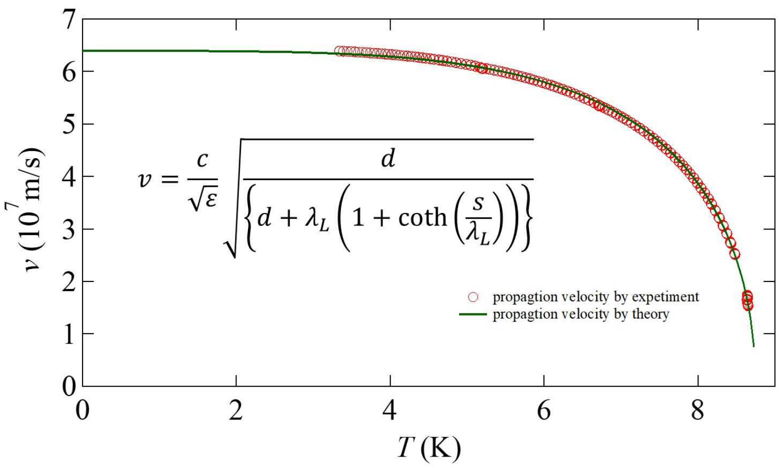

Fig. 1. The propagation velocity in the CB-KID as a function of temperature. Solid line is a fit by the Maxwell-London theory.

Keywords: Kinetic inductance detector, Propagation velocity, Maxwell-London theory

EDP2-4

1 dimensional X-ray imager utilizing a superconducting strip line with a delay line structure

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Now days, Resonant Inelastic soft X-ray Scattering (RIXS) technique have been eagerly developed to study the electrical state of transition metal oxide which shows interesting character such as high-T_c superconductivity and giant magneto resistive effect. In addition, since RIXS utilizes resonant excitation of electrons, it is expected to analysis electrical state with higher resolution because of the larger signal amplitude.

Generally, the luminescence X-ray spectra are detected by the combination of a grating and an image detector such as a CCD camera in order to measure them with higher energy resolution than by ordinal wavelength dispersion type X-ray spectrometers based on semiconductors. However, sufficient spatial resolution (<1 mm), for analysis of such as high-T_c superconductors, can not be obtained by X-ray CCD detectors based on semiconductors. On the other hand, sub mm spatial resolution of 1D-photon imaging was obtained by the combination of the superconducting strip photon detector (SSPD) and the delay line structure [1].

Therefore, we tried to develop 1D-delay line photo imager utilizing SSPD which has 0.5 mm spatial resolution and large active area (> 5 x 10 mm^2). In order to validate if such a structure can work, we calculated the distributed circuit consisting of 10,000 segments of LC which explain a superconducting strip line (width: 400 nm, length: 1 m). As a result, since we obtained the sharp signal rise time which is less than 1 nsec, we found that it is expected to get sufficient spatial resolution for RIXS.

Reference [1] Qing-Yuan Zhao *et al.*, Nat. Photon. **27**, 247 (2017).

Keywords: Superconducting Strip Photon Detector, X-ray detector, RIXS

EDP2-5

Study for the Operating Principle of Superconducting Strip Photon Detectors (SSPDs)

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Superconducting strip photon detectors (SSPDs) are promising single photon detectors for realizing practical quantum cryptography; their high quantum efficiencies, low timing jitters, and low dark count rates overcome those of avalanche photo diodes or other single photon detectors. Recently, some research groups have established testbeds for quantum cryptography and succeeded in field tests of quantum key distribution at a speed of sub Mbps using practical optical fibers in the length of tens of km.
However, the detecting mechanism of the SSPD is still under investigation. The most probable hypothesis is the followings: (1) an incident photon fluctuates the order parameter of a superconducting strip resulting in the nucleation of vortex-antivortex pairs; (2) vortex pairs are unbound and forced out of the strip in the perpendicular direction of bias current; (3) kinetics of vortices forms a normal band across the strip and a current pulse flows out of the strip. Conventional SSPDs utilize the current pulse as a photon detection signal and its response characteristics such as a response time of several ns regulate the quantum communication speed of sub Mbps as mentioned above.
On the other hand, the numerical simulations have shown that the time scale of kinetics of vortices is in the range of ps. Therefore, by detecting the extruded vortices instead of current pulse, we could expect the communication speed faster than several orders of magnitude of that realized by conventional SSPDs. In this study, we have directly connected a superconducting strip with single flux quantum (SFQ) circuits to capture the extruded vortices out of the strip. Since the information carriers of SFQ circuits are also vortices, not only capturing the vortices but also counting the number of the vortices or other logical operations are possible.

Keywords: SSPD, SFQ

EDP2-6

HTS Filter with Dielectric Rods For Tuning the Center Frequency and Trimming the Passband Characteristics

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Tunable filters are one of the most essential microwave components for multiband communication systems due to their attractive features. In this study, we developed high-temperature superconducting (HTS) tunable microstrip line filter with dielectric rods for tuning the center frequency and trimming the passband characteristics simultaneously. Several dielectric rods are placed above the HTS filter, and the center frequency and passband characteristics are controlled by changing the distance between the dielectric rods and resonators. Two dielectric rods are used for a resonator; one is located on the center of the resonator to tune the center frequency and trim the passband characteristics, and the other is located on the open end of the resonator to tune the center frequency. The filter was designed to have a center frequency of 1.4 GHz and a bandwidth of 28 MHz by using an electromagnetic simulator based on the moment method. The HTS filter was fabricated using double-sided $YBa_2Cu_3O_7$ thin film on a 30×40×0.5 mm Al_2O_3 substrate. The dielectric rods with a dielectric constant of 40 were used. Figure 1 shows frequency responses of the tunable filter as a function of distance between the resonator and dielectric rods. The tuning range of the filter was about 140 MHz while keeping the all most the same insertion loss with trimming. The measurement data after trimming and tuning have a good agreement with the design specifications.

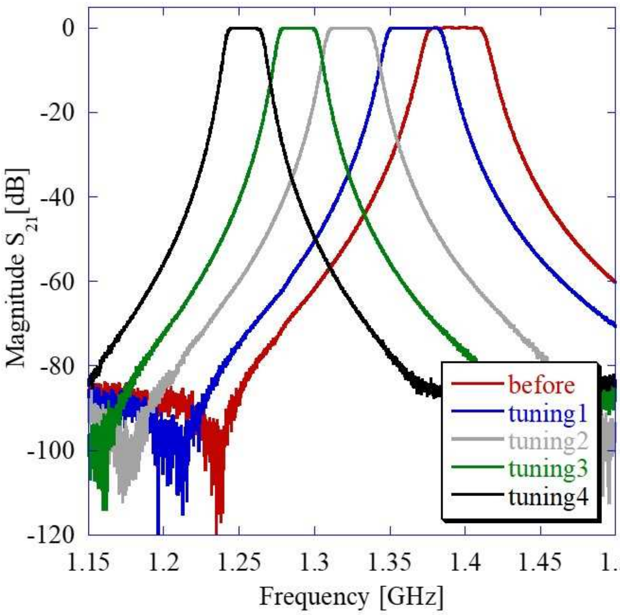

Figure 1 Measured tunability of 4-pole tunable filter before and after tuning.

Keywords: High-temperature superconducting (HTS), tunable bandpass filter,, dielectric rods, microstrip filter

EDP2-7

Design of wireless power transfer system from HTS spiral coil to copper spiral coil

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We have designed a wireless power transfer (WPT) system with high temperature superconducting (HTS) transmit coil and copper receiving coil. The WPT system was designed with bandpass filter theory. The WPT system is consisted of HTS spiral coil, copper spiral coil and two input and output loop coils. The HTS spiral coil was used a double-side HTS tape wire which we proposed before [1]. The center frequency of the WPT system is about 10 MHz. Vector network analyzer was used to measure the frequency response of the WPT system. To design the WPT system, we measured coupling coefficient between spiral coils and external coupling between spiral coil and loop coil. The measured quality factor of the HTS and copper coils are 3200 and 980, respectively. Figure 1(a) and (b) show the measured frequency responses of the WPT system with HTS transmit coil and copper coil and with two copper coils in 50-cm distance between two coils. Good frequency responses were obtained. The transfer efficiency of the WPT systems calculated from Fig. 1(a) and (b) is 73.6 and 61.5 %, respectively.

[1] N. Sekiya, Y. Monjugawa, "A novel REBCO wire structure that improves coil quality factor in MHz range and its effect on wireless power transfer systems," IEEE Trans. Appl. Supercond. vol. 27, 6602005, 2017-6.

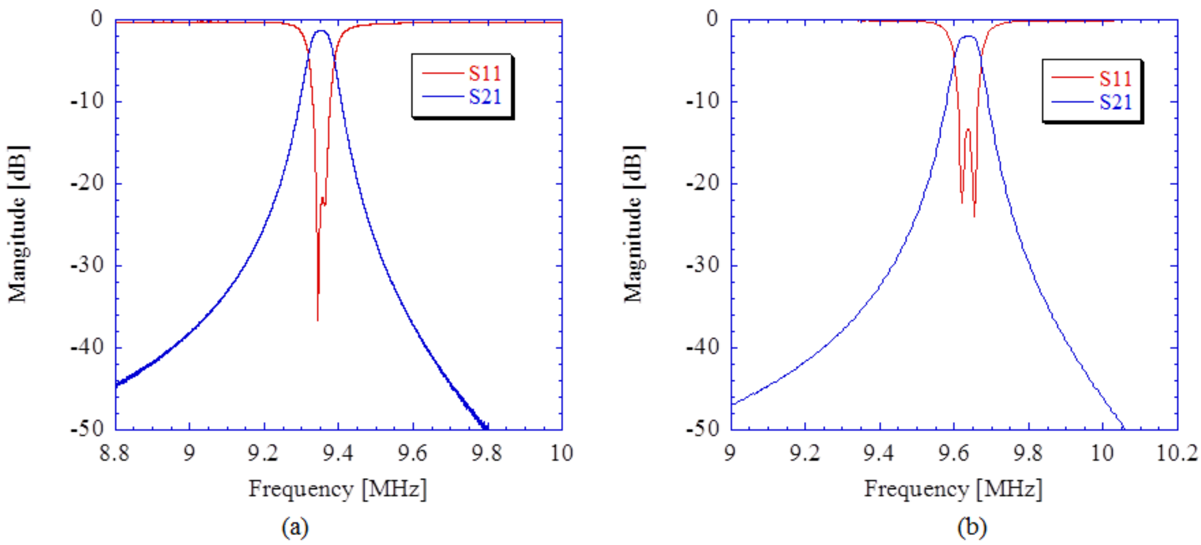

Fig. 1. Measured results of frequency responses in 50-cm distance. (a) HTS transmit coil and copper receiving coil. (b) Two copper coils.

Keywords: wireless power transfer, high temperature superconducting, spiral coil

EDP2-8

Pico Pulse Response Analysis of High-Tc Josephson Weak-Link using Time Dependent Ginzburg-Landau Model

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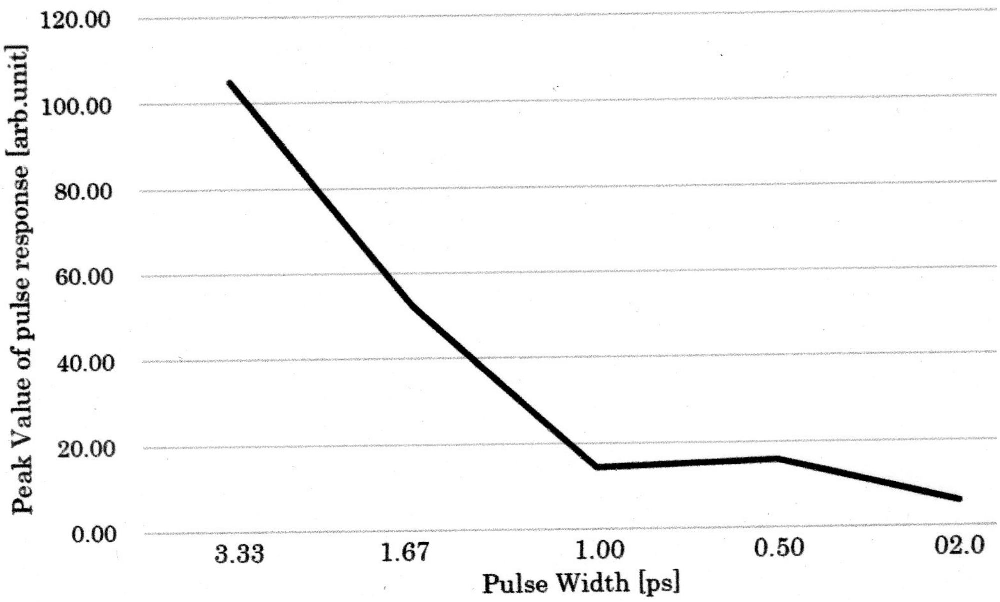
In this paper, we report on the pico pulse response analysis of high Tc superconducting Josephson weak-link in the terahertz region. We assumed $Bi_2Sr_2Ca_2Cu_3O_{10}$ as high Tc superconducting material. Tc and coherence length of $Bi_2Sr_2Ca_2Cu_3O_{10}$ are 110[K] and 1[nm], respectively. Terahertz wave is the electro-magnetic wave whose frequency is ranging from 0.1 to 10 THz and is going to be useful for high speed and high capacity telecommunicating, imaging, biological and chemical analyzing.

Since the photon energy of terahertz radiation is greater than the energy gap of high Tc superconductor, we used the one dimensional time-dependent Ginzburg–Landau (TDGL) equation. For example, pico pulse signal of 0.5[ps] wide consists of harmonic component greater than 10[THz]

We derived the TDGL model as the equivalent circuit of Josephson weak-link by use of the TDGL equation, instead of the RSJ model [1]. In our analysis, Rn, normal resistance of the Josephson weak-link at T>Tc is assumed to be 1[Ω] and pulse response is normalized by the IcRn product where Ic is the critical current of the Josephson weak-link. Following results were found.

The normal resistance of the Josephson weak-link at T<Tc is not constant but dependent on the applied
voltage.
The cosine φ term with negative sign appears in the TDGL model.
We analyzed pico pulse response at 50[K] and found that peak of pulse response decreased when the pulse width became short as shown in Fig.1.

[1] S. Yoshimori, T. Terashima and M. Kawamura, Infrared Physics & Technology, Vol.39, pp.41-45(1998).



Keywords: THz region, High-Tc Josephson weak-link, TDGL model, pico pulse response

EDP2-9

Microfabrication of MgB_2 by a conventional lift-off process

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MgB_2 is a superconductor with a remarkably high superconducting transition temperature T_c= 39 K [1] and an extremely short electron-phonon scattering time $\tau_{e-ph} \simeq$ 3ps [2]. These characteristic features have impacts on not only basic research but also applied physics. However, a convenient microfabrication method applicable to MgB_2 has not been established yet because of the lack of a thin film growth process without heating up. Recently, we have succeeded in epitaxial growth of MgB_2 thin film with Mg buffer layer under a significantly low substrate temperature of 110 ℃ by using a molecular beam epitaxy (MBE) method [3]. The MgB_2 thin films thus obtained exhibits superconductivity with T_c = 27 K in spite of such low growing temperature. We demonstrate a microfabrication by a conventional lift-off process using an organic photoresist (Clariant AZ 5214 E) for MgB_2 thin films growen at low temperatures.
The Mg buffer layer of 24-nm thick was deposited with the deposition rate of 1.3×10^{-2} nm/min on a photoresist-patterned sapphire substrate by using the MBE method. After the Mg buffer layer deposition, the 96-nm thick MgB_2 layer was deposited under ultra-high vacuum of 3.3×10^{-7} Pa with the deposition rate of 3.8×10^{-2} nm/min by the co-evaporation of Mg and B, which were deposited by the Knudsen cells. The deposition rate ratio between Mg and B was the same as the exact stoichiometric ratio of Mg:B = 1:2. A 53-nm thick Bi layer was deposited on top of the MgB_2 film as a passivation layer. We successfully fabricated a 100-m stripline of MgB_2 by a conventional lift-off process and confirmed the superconductivity below 20 K.

[1] J. Nagamatsu *et al.*, Nature **410**, 63 (2001).
[2] B. B. Jin *et al.*, Supercond. Sci. Technol. **18**, L1 (2005).
[3] H. Shishido *et al.*, App. Phys. Express **8**, 113101 (2015), H. Shishido *et al.,* J. Phys.: Conf. Series **871**, 012036 (2017).

EDP2-10

Replacement of NbN by $YBa_2Cu_3O_{7-\delta}$ in Superconducting Thin Film Coil in a Spiral Trench on a Si-Wafer for Compact SMESs

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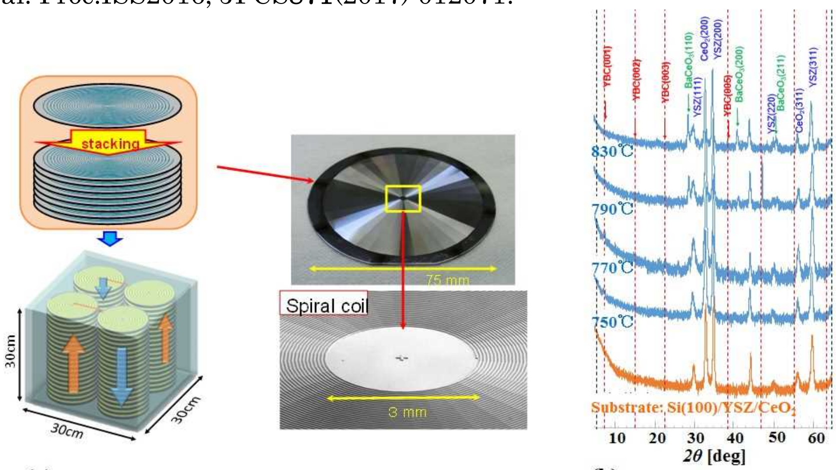
We have been developing superconducting thin film coils in a spiral trench on a Si wafers for compact SMESs as shown in Fig.(a). A proof of concept has been performed using NbN thin films showing energy storage of 0.01 mJ [1]. Increasing NbN thickness by mitigating film stress, the stored energy increased up to 0.1 mJ [2]. For further improvement, we moved on to replacement of NbN by $YBa_2Cu_3O_{7-\delta}$. Firstly, sputter- deposition of yttria stabilized zirconia succeeded by CeO_2 has been performed to form buffer layers to grow c-axis oriented $YBa_2Cu_3O_{7-\delta}$. By tuning the deposition conditions, (100) preferred orientations were attained in both layers. Deposition of $YBa_2Cu_3O_{7-\delta}$ was performed by metal organic deposition (MOD) using a commercially available raw material for MOD: KOJUNDO CHEMICAL LAB, YBC-05(1/2/3). The post deposition annealing (PDA) for 90 min in 1000 ppm O_2/N_2 was followed by annealing at 500 ℃ for 100 min in pure O_2. PDA at 830 ℃ resulted in formation of $BaCeO_3$ as shown in Fig.(b). By decreasing PDA temperature, c-axis oriented $YBa_2Cu_3O_{7-\delta}$ emerged while $BaCeO_3$ faded out. To enhance the c-axis orientation of the MOD film, sputter-deposition of $YBa_2Cu_3O_{7-\delta}$ prior to MOD was also examined. More detailed findings and points obtained for the replacement of NbN by $YBa_2Cu_3O_{7-\delta}$ are to be analysed.
This work is partly supported by NEDO (16101979-0)[1] N.Sugimoto et al.SUST**30** (2017) 015014.
[2] Y.Suzuki et al. Proc.ISS2016, JPCS**871**(2017) 012071.



(a) (b)

Fig.(a) Superconducting coil composed of 4 units. Each of the units is made of stacked Si wafers engraved with a superconducting thin film coil in a spiral trench formed with MEMS technology. (b) X-ray diffraction patterns of $YBa_2Cu_3O_{7-\delta}$ films on sputter-deposited CeO_2/YSZ thin film buffersa t different post-deposition annealing temperatures

Keywords: SMES, Si wafer, NbN, YBa2Cu3O7-δ

EDP2-11

Numerical Analysis of Rapid Single-Flux-Quantum Circuits Composed of 0- and π-Shifted Josephson Junctions

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We report numerical analysis of rapid single-flux-quantum (RSFQ) circuits using combination of 0- and π-shifted Josephson junctions. The π-shift in phase difference is observed in several types of Josephson junctions, for example, a sandwich structure of superconductor electrodes and a ferromagnetic thin layer. We use a dc-SQUID including 0- and π-shifted Josephson junctions as a basic element, where bistability is obtained by the persistent current in either the counterclockwise or clockwise direction. This can lead to the following features: (1) reduction in power consumption with less bias points, (2) efficient circuit designs with a fewer number of junctions, and (3) smaller circuit areas because of eliminating large-inductance superconductor loops to store magnetic flux quanta, which are required in conventional RSFQ circuits to represent binary information.

We obtained successful operation of a toggle flip-flop (TFF) that was composed of two Josephson junctions (J_0, P_1) as shown in Fig. (a). The P_1 and P_2 are π-shifted junctions, while J_0 and J_3 are normal (0-shifted) junctions. The input signals provided from a dc-SQUID (P_2, J_3) were divided to the two outputs as shown in Fig. (b). Our numerical simulation showed that the efficient TFF could be constructed with half the number of junctions with no bias current ports, and the bias currents to P_2 and J_3 could be reduced to approximately 2/3, compared with the conventional RSFQ TFF and Josephson transmission line.

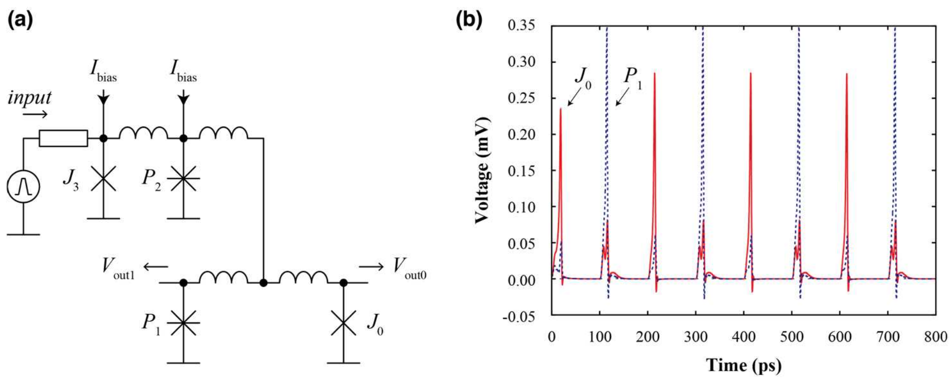

Fig. (a) equivalent circuit of a toggle flip-flop, (b) output signals. The inductance L, Josephson critical currents I_c, and bias currents I_{bias} are 2 pH, 200 μA, and 90 μA, respectively.

Acknowledgment: This work was supported by Grant-in-Aid for Scientific Research A (16H02340). The authors would like to thank Yuki Yamanashi for help in the numerical simulating.

Keywords: π Josephson junctions, rapid single-flux-quantum, low-power consumption, efficient circuit design

EDP2-12

High Impedance Josephson Junction Arrays for Voltage Standard Circuits.

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For voltage standard circuits, tens of thousands Josephson junctions connected in series consist of a co-planar waveguide, and microwaves or pulse codes are applied to them to generate the Shapiro step [1-2]. Both the larger output voltage (the number of junctions N) and the larger operating margin (the step height) are required. However, the large number of the junction N decreases the operating margin due to dissipation for applied microwaves in the junction, because microwave power P at N-th junction is given by $P = P_0 \exp(-N R_N/Z)$, where R_N is the junction resistance.
We designed the characteristic impedance of the array Z to be 100 W, while that for the conventional one was 50 W as shown in Fig.(a), because the high impedance array might contribute to increase the operating margin due to the smaller electric loss across the array. As shown in Fig.(b), the array including 19,199 Josephson junctions generated the flat voltage step at about 0.4 V, that suggested the array was working properly.

[1] S.P.Benz et al., IEEE Trans. on Appl. Supercond., Vol.25, p. 1300108 (2015).
[2] M.Maruyama et al., J. of Phys. Conf. Series, Vol.234, p.042020 (2010).

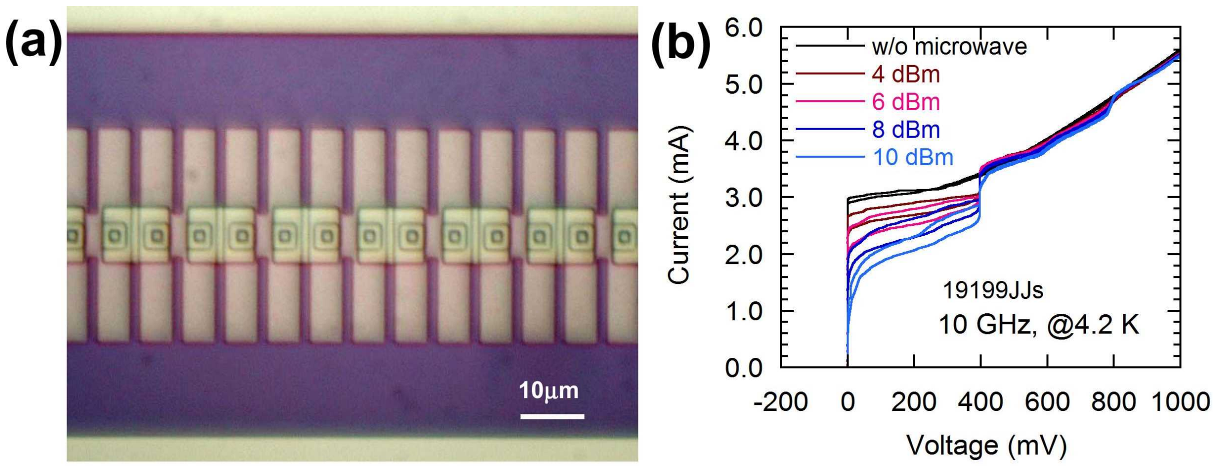

Fig. (a) Fabricated Josephson junction array, the junction size is 3 mm, (b) measured I-V characteristics for 19,199 NbN/TiN/NbN Josephson junctions with different microwave powers of 10 GHz at 4.2K.

The devices were fabricated in the clean room for analog-digital superconductivity (CRAVITY) in National Institute of Advanced Industrial Science and Technology (AIST). This work was partially supported by JSPS KAKENHI Grant No. 17K06481.

Keywords: Voltage Standard, NbN, CPW, Shapiro Step

EDP2-13

Negative resistance in niobium titanium nitride nanowires for flux-based superconducting devices

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Superconducting devices on nanowire have attracted much attention owing to easy fabrication. Because the nanowires do not use an insulating tunnel barrier, such as Josephson junction and their critical current is tuned by the wire diameter. We present temperature dependence of resistance and current-voltage characteristics of niobium titanium nitride (NbTiN) nanowire with different width and length. Firstly, superconducting NbTiN films were firstly prepared by deposition at ambient temperatures on (100) MgO substrates. The NbTiN nanowires were fabricated from 2D films with thickness $d = 5$ nm by a conventional e-beam lithography method and a reactive ion etching method with CF_4 plasma. As a result, we observed negative current-voltage characteristics (n-IVC) as a function of magnetic field due to field induced superconductivity. One of reasons for n-IVC is based on the suppression of the non-equilibrium charge imbalance process at normal and superconducting boundaries, namely, at the boundaries between phase-slipped and superconducting regions in SNWs. Although the exact mechanism is unsolved, it is reasonable to consider that the one of the reason for n-IVC concerns with the existence of phase slip centers originating the behaviors of Thermal activation phase slip (TAPS) and/or quantum phase slip (QPS). In addition, we will argue observed the n-IVC is caused by entry of vortices in the nanowire. We also propose a concept of flux-based superconducting devices without using the nanowires.

Keywords: nanowire, phase slip