Design and Fabrication of Microwave Kinetic Inductance Detectors using NbN Symmetric Spiral Resonator Array

K Hayashi[1], A Saito[1], Y Ogawa[1], M Murata[1], T Sawada[1], K Nakajima[1], H Yamada[1], S Ariyoshi[2], T Taino[3], H Tanoue[3], C Otani[4], and S Ohshima[1]

[1] Graduate School of Science and Engineering, Yamagata University, 4-3-16 Jonan, Yonezawa, Japan

[2] Graduate School of Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya, Japan

[3] Graduate School of Science and Engineering, Saitama University, 255 Okubo, Sakura-ku, Saitama, Japan

[4] RIKEN Advanced Science Institute Terahertz Sensing and Imaging Team, 2-1 Hirosawa, Wako, Japan

E-mail: tse80358@st.yamagata-u.ac.jp

Abstract. We designed and fabricated a microwave kinetic inductance detector (MKID) using a niobium nitride (NbN) symmetric spiral resonator array. Previously we revealed that a rewound spiral structure works as not only a high-Q half-wavelength resonator but also as a broadband terahertz antenna. We conducted simulations for a 9 resonator array assuming NbN as the superconducting material and sapphire as the dielectric substrate, and obtained a maximum attenuation of over 30 dB and unloaded quality factors of over 2×10^5 for frequencies between 4.4 and 4.9 GHz. We fabricated the 9 resonator array MKID using NbN thin film deposited on an m-sapphire substrate by using dc magnetron sputtering. We observed half-wavelength resonances of around 4.5 GHz at 4 K. We measured the optical response of the MKID. The frequency shift was 0.5 MHz when illuminated with 650 nm photons.

1. Introduction

Microwave kinetic inductance detectors (MKID) [1] are a type of non-equilibrium superconducting photon detector made of high quality factor superconducting microwave resonators which are coupled to a suitable antenna or an absorber structure. MKIDs are powerful detectors for large arrays due to using only a pair of feed lines. Furthermore, they can be easily made with a single layer of superconducting film deposited on a substrate and patterned using conventional optical lithography. Research groups have been developing MKIDs for sub-millimeter astronomy [2], optical astronomy [3], and dark matter detection experiments [4] in recent years. These MKIDs require an operating temperature of 0.1 K, which is attained using expensive dilution refrigerators or adiabatic demagnetization refrigerators. Therefore, there are so far no applications in which MKIDs can be used to perform general-purpose measurements, particularly for terahertz spectrometers. To realize a larger array MKID, we need smaller resonators with a high quality factor, a large attenuation at the resonant frequency, and high efficiency coupling to THz waves. In past studies, Baryshev et al. proposed an antenna-coupled MKID using $\lambda_g/4$ resonators with twin arc slot antennas [5], and Doyle et al. proposed a lumped-element MKID (LEMKID) [6]. Previously we identified a similarity between the structures

of a spiral terahertz antenna [7] and a rewound spiral microwave resonator [8] and proposed an MKID using a rewound spiral resonator (spiral-MKID) [9]. Recently, we proposed the use of symmetric spiral resonators for an MKID array, feasible for the realization of large arrays in electromagnetic simulations [10]. We foresaw the use of spiral-MKID operating at 4 K by using a niobium nitride (NbN) thin film. However, it has not been verified experimentally yet. In this experiment, we verified that a symmetric spiral resonator is feasible for large arrays. We fabricated a 9 resonator array MKID using an NbN spiral resonator array and measured the frequency and optical responses of the MKID at 4 K.

2. Resonator and array designs

We designed an MKID with rewound spiral resonators. Fig. 1 illustrates the design of a 9 resonator array spiral-MKID. Enlarged view shows one pixel of the spiral resonator. The frequency responses of the resonators were simulated using an electromagnetic simulator (Sonnet-EM software) on the basis of the finite integral method. We assumed the simulation parameters using an NbN thin film as the superconducting film and m-plane sapphire as the dielectric substrate. We defined a function for the RF resistivity (R_{rf}), which is directly proportional to the square of the frequency. Surface resistances (R_s) of the NbN films were measured using the dielectric resonator method at 21.8 GHz. We found that R_s = 0.19 mΩ at 21.8 GHz and 4.2 K. Then, an R_{rf} of 3.924 × 10^{-26} ΩHz^2/sq was used in simulations. A kinetic inductance value of 1.225 pH/sq was used for the simulation. Conventional coplanar waveguides (CPWs) without a ground plane were selected as the readout through the line. The width of the signal line and gap were 40 and 10 μm, respectively, corresponding to a specific impedance of 50 Ω. The spiral resonator was placed into the space near the signal line from which the ground plane of the CPW was removed. The size of the 12-turn spiral resonator was 480 μm square. Both the width of the line and space of the resonator were 10 μm. The total length of the resonator was adjusted to that of the effective guided half-wavelength. The distance between ground and resonator was 30 μm.

Fig. 2 shows the simulated transmission (S_{21}) response of a spiral resonator for the spiral-MKID. We observed a sharp resonance around 4.498 GHz and obtained maximum attenuation (A_{max}) of over 20 dB and an unloaded quality factor (Q_u) of over 5×10^4. Fig. 3 shows the current density distribution of a spiral resonator at 4.49824 GHz. The white and black areas represent higher and lower current density, respectively. The current is concentrated in the central part of the resonator, which means there is an effective guided half-wavelength resonance.

To realize large array spiral-MKIDs, frequency characteristics of all resonators with different resonant frequencies should be equal. We designed two models with different couplings between the signal line and the resonators, namely, an asymmetrical and symmetrical model shown in Figs. 4(a) and (b), respectively. The length of the resonators was varied for every 100 μm increment, which caused a frequency shift of around 30 MHz [10]. Fig. 5 shows the dependence of Q_u for the respective resonances. We obtained a Q_u of over 5×10^4 in both models. As resonant frequency of the resonator increased, the Q_u decreased in the asymmetric model shown in Fig. 4(a). On the other hand, we obtained a Q_u of approximately 4×10^4 for all resonators in the symmetric model shown in Fig. 4(b). Fig. 6 shows the simulated S_{21} responses of the 9 resonator array spiral-MKID. According to the preceding results, we found that the symmetric spiral resonator was superior to the asymmetric resonator concerning microwave response.
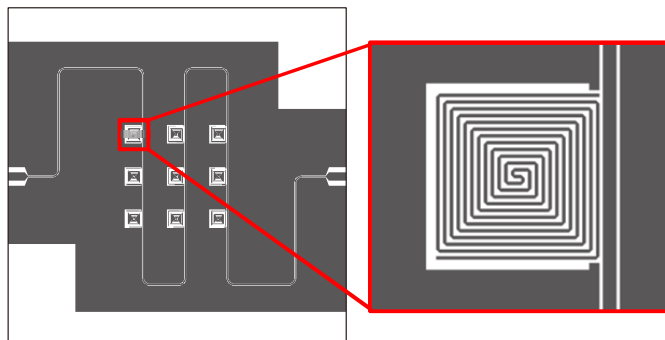

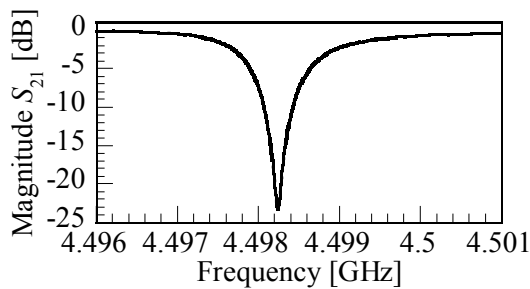**Figure 1.** Typical patterns of 9 resonator array spiral-MKID. Enlarged view is the rewound spiral resonator.

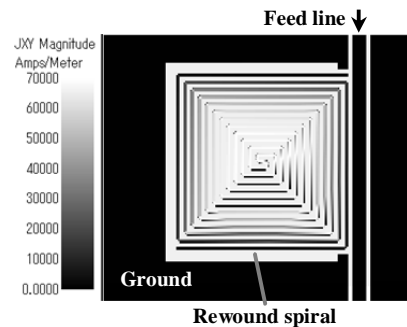**Figure 2.** Simulated microwave response of rewound spiral resonator.

Figure 3. Current density distribution of spiral resonator at 4.49824 GHz.
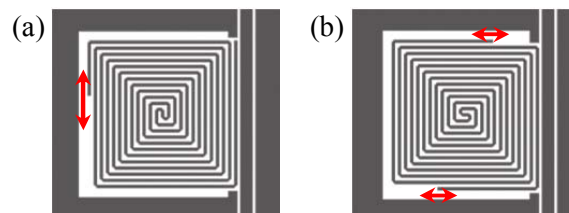

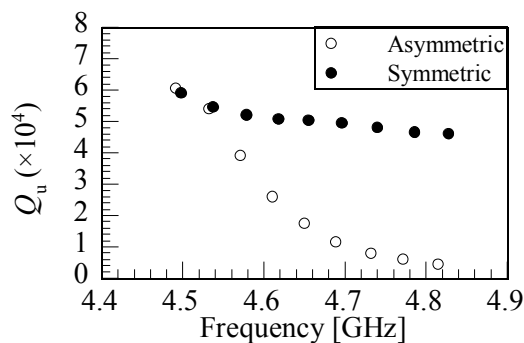**Figure 4.** Schematic of spiral-MKIDs. (a) Asymmetric model. (b) Symmetric model.

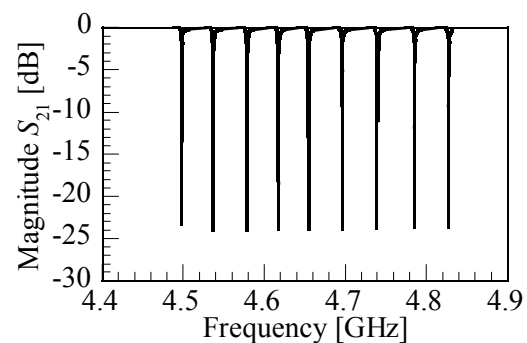**Figure 5.** Dependence of unloaded quality factor for respective resonators.

Figure 6. Simulated microwave response of 9 resonator array MKID using symmetric spiral resonator.

3. Experiments

3.1. Fabrication and measurement of MKID array

We selected NbN films for the fabrication of the spiral-MKID. The films were deposited on m-plane sapphire substrates using reactive DC magnetron sputtering with a discharge current source. The sputtering conditions of the films were investigated by varying the gas ratio of Ar and N_2 for the same current, and a suitable T_c of 16 K was obtained for an NbN film with a thickness of 150 nm on an m-plane sapphire substrate. The 9 resonator array spiral-MKID was patterned using standard photolithography and reactive ion etching, as shown in Fig. 4(b). The MKID chip was mounted to a polychlorinated biphenyl (PCB) chip carrier ($\varepsilon_r = 11.6$) coated on both sides with Au films and bonded using Al wires (ϕ 25 μm). The chip carrier was placed in a cryocooler and we measured the resonance frequency, the A_{max}, and the quality factor of the spiral-MKID. We measured at 4 K since we target to an application for general-purpose measurements. The microwave response, S_{21}, passing through a cryogenic low-noise amplifier (LNA) was measured using a vector network analyzer (VNA).

3.2. Frequency and optical responses

Fig. 7 shows the S_{21} response of the 9 resonator array spiral-MKID measured at 4 K without calibration. 9 resonances are clearly shown in the frequency range of 4.4 to 5.0 GHz at 4 K. There is a difference in the interval of resonant frequency. The reason for the different interval is still under investigation.

Fig. 8 shows the optical response of a single resonator measured at 4 K. The solid line indicates the S_{21} response of the spiral-MKID when illuminated with 650 nm photons, and the dotted line indicates the response without optical illumination. The frequency shift of 0.5 MHz is clearly observable. This result suggests that the spiral-MKID is capable of detecting terahertz waves.
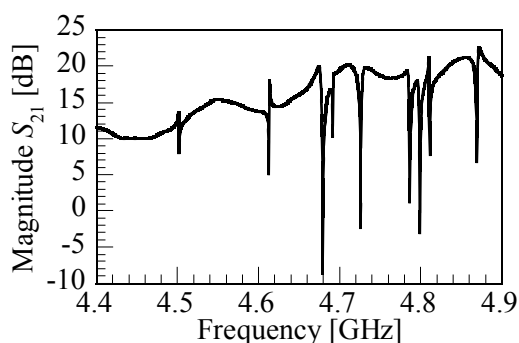

Figure 7. Microwave response of 9 resonator array MKID using a symmetric spiral resonator.
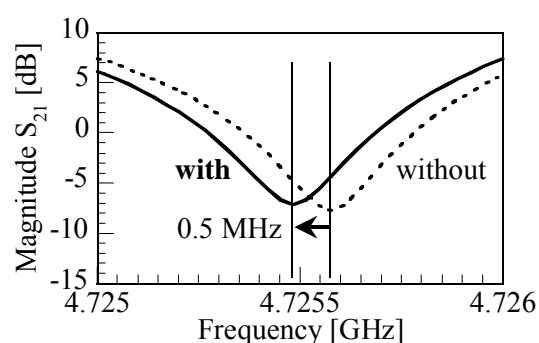
Figure 8. Optical response of single resonator.

4. Conclusions

We designed and fabricated a 9 resonator array MKID using an NbN symmetric spiral resonator, and then we measured the frequency response of the MKID. We observed 9 resonances of the S_{21} response. The frequency of 0.5 MHz was observed when illuminated with 650 nm photons. The preceding results suggest the spiral-MKID is capable of detecting terahertz waves.

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