Linewidth dependence of NbN-based microwave kinetic inductance detectors

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Abstract. We analysed, fabricated, and characterised niobium nitride (NbN)-based microwave kinetic inductance detectors (MKIDs) with a rewound strip structure (spiral-MKIDs). To control resonance characteristics precisely, the linewidth (w) dependence of rewound spiral resonators varying between w = 10, 20, and 40 μm was analysed using an electromagnetic field simulator; the resonance frequencies (f₀'s) were obtained as 4.42, 4.58, and 5.15 GHz respectively, proving that the inductance decreases as the w increases. To verify the simulation results experimentally, NbN-based MKID arrays with different linewidths were fabricated on 10×10 mm² sapphire substrates, and cooled down to 3 K. The microwave characteristics with a vector network analyser, and f₀’s were found to be 4.11, 4.23, and 4.85 GHz for the MKIDs with w = 10, 20, and 40 μm, respectively. These values are in agreement with the simulation results within 7.6% accuracy. The other resonance characteristics such as the scattering-matrix element (S21) and loaded quality factor (Q_L) showed the similar w dependence with the simulation. Spiral-MKIDs with narrower w is expected to have better detector performance owing to shallower S21 and higher Q_L.

1. Introduction

Terahertz waves—frequency range of 0.1–10 THz—exhibit the transparency of radio waves and straightness of light waves simultaneously. Terahertz wave detection has been used for non-invasive and non-destructive imaging inside an object application. Recent advances in terahertz wave technology are expected to be applied in various fields, such as medical science, security, and agriculture [1]. The microwave kinetic inductance detector (MKID) [2] detects terahertz waves when the kinetic inductance of a superconducting film changes due to the absorption of a terahertz photon. The MKIDs consist of multiple resonators coupled with a microwave through-line, where the resonance frequency shift of each resonator is detected by the frequency-multiplexed readout scheme. All of the components in MKIDs are made up of a single-layer film, which enables relatively easy fabrication of a large-scale array. Many other groups [3] have been developing MKIDs to achieve ultimate sensitivity performance mainly used for astronomical observations. In these detectors, low transition temperature (Tc) materials, such as Al [4] or TiN [5], are commonly employed. However, their operations require expensive and/or large cooling systems employing a dilution refrigerator (0.1 K) or closed-cycle ³He sorption pump (0.3 K).
On the other hand, NbN material can provide relatively high sensitivity performance at 3 K; this temperature becomes easily achievable using a compact ⁴He refrigerator.

In this study, we describe NbN-based MKIDs with rewound spiral resonators (spiral-MKIDs) operated at 3 K. The linewidth dependence of rewound spiral resonators is analysed using an electromagnetic field simulator. We then explain the fabrication of the spiral-MKIDs and characterise the electrical performance of the detector from the following perspectives: resonance frequency, scattering-matrix element, and loaded quality factor.

2. Detector design and analysis

Electromagnetic field analysis is useful for effective optimisation of the MKID design. To control resonance characteristics precisely, the linewidth dependence of a rewound spiral resonator [6-8] was analysed via a simulator, Sonnet Lite. Figure 1 shows a resonator designed from the analysis model [9]. The total length of the spiral is approximately 12.5 mm corresponding to the half wavelength of the resonance frequency of around 5 GHz on the sapphire substrate. Coplanar waveguide (CPW) through-line is employed for the excitation and readout. The line and gap widths of the through-line are 40, and 10 μm respectively, which corresponded to a specific impedance of 50 Ω.

![Figure 1. Analysis model of one-pixel spiral-MKID (bird’s-eye view).](image)

Dark and light regions are the NbN film and sapphire substrate, respectively.

The analysis was conducted under the following conditions: frequency range of 1–10 GHz; relative permittivity of the substrate, 9.8; substrate thickness, 0.5 mm; thin film (100 nm) AC resistance, $R_{dc} = 5.88 \times 10^{-26}$ Ω Hz⁻²/sq; and sheet inductance, $L_S = 1.838$ pH/sq, where the $R_{dc}$ and $L_S$ were recalculated from previously reported values obtained at thickness of 150 nm thickness [10]. The analytical model is defined to be surrounded by air at the upper space and silicon at the lower space of the substrate. Resonance characteristics were analysed on the three resonator models with a fixed line space, $a = 10$ μm and linewidth ($w$) varying to 10, 20, and 40 μm, giving the resonator size of 500×500 μm², 650×650 μm², and 800×800 μm², respectively. Figure 2 (a) shows the simulation results of microwave resonance characteristics. The resonance frequencies ($f_0$'s) obtained were 4.42, 4.58, and 5.15 GHz respectively, proving that the inductance decreases as the resonator linewidth increases. The $f_0$ simulated for the MKID with $w = 40$ μm was blue-shifted by 0.73 GHz compared with that for 10 μm. The scattering-matrix element ($S_{21}$) and loaded quality factor ($Q_L$) were also analysed for each $w$ and shown in Figure 2 (b). $Q_L$ was obtained from the $f_0$ and its resonance dip width ($\Delta f$), which is defined as $Q_L = f_0 / \Delta f$. $S_{21}$ values were found to be -30.1 dB for $w = 10$ μm, -39.5 dB for $w = 20$ μm, and -45.7 dB for $w = 40$ μm at the resonance dip; thus, narrower the $w$ is the shallower the $S_{21}$. On the contrary, the narrower the $w$ higher the $Q_L$ with individual $Q_L$ values as 4020 for $w = 10$ μm, 2230 for $w = 20$ μm, and 970 for $w = 40$ μm. The simulation results revealed that spiral-MKIDs with narrower linewidths are expected to have a better detector performance owing to larger $S_{21}$ and higher $Q_L$. 


3. MKID fabrication
To verify the simulation results experimentally, we deposited a 100 nm thick NbN film on a sapphire substrate using DC magnetron sputtering. Spiral-MKIDs with three different linewidths ($w = 10, 20, \text{ and } 40 \, \mu m$) were then fabricated using a standard photolithography and Ar-ion etching. Figure 3 shows a 25-pixel prototype array on a $10 \times 10 \, mm^2$ sapphire substrate and an enlarged image of a single pixel. Both sides of the through-line and edges of the resonators are grounded at the same plane. The resonator length of each detector pixel differs by $30 \, \mu m$ and is connected to a single signal readout line by capacitive coupling, as this configuration is capable of the frequency-domain multiplexing.

![Figure 3. NbN-based MKID array fabricated on a sapphire substrate (left). Enlarged image of a single pixel (right). In the right image, yellow and gray regions are the NbN film and sapphire substrate, respectively.](image-url)
4. Electrical evaluation
The fabricated MKID chip was mounted on a cryostat based on a $^4$He pulse tube refrigerator and cooled down to 3 K. Microwave resonance characteristics of each detector chip were evaluated using a vector network analyser. The output power of the network analyser was set to -40 dBm. The transmission signal was measured through a cryogenic high-electron-mobility transistor amplifier and ambient temperature amplifier with a gains of 30 dB and 28 dB, respectively, to achieve low-noise measurements.

Figure 4 (a) shows the microwave resonance characteristics of the 25-pixel MKID array with $w = 10 \mu m$ measured at 3 K without calibration. The half-wavelength resonance dips were clearly observed in the frequency range from 4.11–4.40 GHz; the frequency interval between adjacent pixels was 13 MHz with a standard deviation of 3 MHz. For $w = 20 \mu m$ (Fig.4 (b)) and 40 $\mu m$ (Fig.4 (c)), their resonance dips were shifted to the higher frequency range such as 4.23–4.62 and 4.85–5.48 GHz, respectively. This frequency shift can be explained from the general behavior that the inductance decreases with increasing linewidth ($w$), and the resonance frequency is inversely proportional to the square root of the inductance (i.e. $f = \frac{1}{2 \pi \sqrt{LC}}$). Figure 4 (d) shows the linewidth dependence of $S_{21}$ and $Q_L$ extracted from the resonance data. The linewidth difference is observed not to affect $S_{21}$ experimental results. The $Q_L$ becomes higher at a narrower linewidth. This is because the narrower linewidth which weakens the coupling strength between the detector edge and readout through-line. On the other hand, the $Q_L$ of 1240

![Figure 4](image-url)
for 10 μm, for example, is lower than previously reported results—2000 (at 150 nm, 4 K) [10] and 16000 (at 140 nm, 3.2 K) [9].

Table 1 summaries the comparison of simulation and experimental results. The values of $f_0$ match the simulated results within 7.6 % accuracy to the maximum, and the frequency shift (0.74 GHz) between $w = 10$ and 40 μm is also in good agreement with the simulated result (0.73 GHz). The values of $S_{21}$ and $Q_L$ is calculated by averaging all of the resonance characteristics. However, the discrepancy for $S_{21}$ and $Q_L$ is relatively large compared with that of $f_0$. This is probably caused by the NbN film quality such as transition temperature and residual resistance, which strongly affects the resonance shape. Deposition of the higher quality film as well as optimisation of the fabrication process are expected to improve the detector performance such as noise equivalent power and response speed.

Table 1. Comparison of simulation and experimental results for each linewidth

| Linewidth (μm) | Average resonance frequency $f_0$ [GHz] | Average scattering-matrix element $S_{21}$ [dB] | Average loaded quality factor $Q_L$ [-] |
|----------------|----------------------------------------|---------------------------------------------|-------------------------------------|
| $w = 10$ μm    | Simulation 4.42 (std. dev. 30.1)        | Experiment 4.01 (std. dev. 26.2)             | Simulation 4020 (std. dev. 4020)    |
|                | (Error 7.0%)                             | (Error 9.8%)                                 |                                    |
| $w = 20$ μm    | Simulation 4.58 (std. dev. 39.5)        | Experiment 4.23 (std. dev. 26.9)             | Simulation 2230 (std. dev. 2230)    |
|                | (Error 7.6%)                             | (Error 8.1%)                                 | (Error 850)                         |
| $w = 40$ μm    | Simulation 5.15 (std. dev. 45.7)        | Experiment 4.85 (std. dev. 26.6)             | Simulation 970 (std. dev. 970)      |
|                | (Error 5.8%)                             | (Error 12.5%)                                | (Error 600)                         |

5. Conclusion
To predict the microwave resonance characteristics of spiral-MKIDs prior to the fabrication is one of the important issues for optimising the detector performance effectively. For this purpose, we analysed, fabricated and evaluated NbN-based MKIDs with three different linewidths (10, 20, and 40 μm). The simulated resonance frequency was in good agreement with the experimental results within 7.6% maximum accuracy. In terms of the scattering-matrix element ($S_{21}$) and loaded quality factor ($Q_L$), the experimental results had similar linewidth dependence as that obtained from the simulation. Thus, spiral-MKIDs with narrower linewidth are expected to realise higher sensitivity performance owing to shallower $S_{21}$ and higher $Q_L$. To further confirm our conclusions drawn here, optical measurements such as noise equivalent power and response speed are some of the factors that need to be considered for future studies on these systems.

Acknowledgments
The authors would like to thank Professor Takashi Noguchi (National Astronomical Observatory of Japan) for his valuable suggestions for the development of the detector. This study was partly supported by the Grant-in-Aid for Scientific Research (B) (No. 17H02809) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.
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