Design evaluation of microwave transmission properties of YBa$_2$Cu$_3$O$_7$-based kinetic inductance detectors

Seiichiro Ariyoshi$^1$, Hikaru Mikami$^1$, Atsushi Ebata$^1$, Satoshi Ohnishi$^1$, Takeshi Hizawa$^1$, Saburo Tanaka$^1$ and Kensuke Nakajima$^2$

1 Toyohashi University of Technology, 1-1 Hibarigaoka, Tempaku-cho, Toyohashi, Aichi, 441-8580, Japan
2 Yamagata University, 4-3-16 Jonan, Yonezawa 992-8510, Japan

E-mail: ariyoshi@tut.jp

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Abstract

We designed, fabricated, and characterized microwave transmission properties with rewound strip structures for YBa$_2$Cu$_3$O$_7$ (YBCO)-based kinetic inductance detectors (KIDs). The superconducting rewound strip serves as a microwave resonator and as a broadband terahertz-wave antenna. To predict the microwave resonance characteristics before fabrication, the line-width ($w$) and space ($s$) dependence of the spiral resonators were analyzed using an electromagnetic simulator; the resonance frequency increased, and the quality factor decreased with increasing $w$ and $s$ from 10 to 40 $\mu$m.

YBCO-based KID arrays with different $w$ (10 and 40 $\mu$m) were fabricated on 10 mm-square MgO substrates, cooled to 3 K using a $^4$He refrigerator, and evaluated using a vector network analyzer to verify the result of the simulation experimentally. The measured resonance frequency ratio of 1.11 times ($5.04 \rightarrow 5.59$ GHz) agreed with the simulated ones of 1.10 times ($4.84 \rightarrow 5.33$ GHz) between $w = 10$ and 40 $\mu$m. The other resonance characteristics, such as transmission coefficient and quality factor, have a similar $w$ dependence with the simulation.

1. Introduction

Terahertz waves have a frequency range of 0.1–10 THz (3 and 0.03 mm in wavelength), which is located between the highest frequency with transparency (radio waves) and the lowest with straightness like light waves. Owing to these natures, terahertz waves are expected to be applied for nondestructive and noninvasive imaging in a wide variety of fields such as security, medicine, agriculture, material science and so on [1–4]. Room temperature operated pyroelectric sensors, and semiconductor bolometers are commercially available as broadband terahertz detectors. However, high-sensitive and high-speed detectors with large array capability are still required to accelerate imaging applications.

The kinetic inductance detector (KID) [5], which is a sort of superconducting photon detector, is one of the promising candidates to realize fast terahertz imaging due to its simple fabrication with single layer film and the frequency-domain multiplex readout scheme. KIDs using low transition temperature ($T_c$) materials such as metals (Nb, Ta, and Al [6, 7]) and metallic nitride (TiN$_x$ and NbN [8, 9]) have been well developed over the past two decades for astronomical observations requiring extreme sensitivity; however, it requires expensive cooling systems below several kelvins. High-$T_c$ superconductors, like YBa$_2$Cu$_3$O$_7$ (YBCO) are attractive materials to drive KIDs with higher operating temperatures, although they have lower sensitivity than low one’s $T_c$ materials.

A few development reports of kinetic inductance bolometers using YBCO film [10, 11]; however, the systematic analysis to characterize and control the detector performance is still limited. The performance comparison including other types of YBCO-based detectors such as Josephson junction detectors [12] and transition edge bolometers [13] is summarized in table 1.

In a previous study, we proposed, fabricated, and measured the electrical and optical response of YBCO-based KIDs with rewound spiral resonators in the operating temperature range of 11 K to 50 K [14], where the microwave resonator based on a rewound spiral strip structure [15] is also designed for broadband terahertz...
In this study, we analyze the resonance characteristics of the YBCO–KIDs and compare the simulation results with the fabricated ones. Concretely first, the line-width ($w$) and space ($s$) dependence of the spiral resonators is analyzed using an electromagnetic simulator. Next, we explain the fabrication process of YBCO–KIDs and then characterize the electrical performance. Finally, we describe the resonance frequency, transmission coefficient, and quality factors as simulated and experimental results.

2. Detector analysis

2.1. Simulation setup

To elucidate the microwave resonance behavior of YBCO–KIDs, an electromagnetic field simulation was conducted using the Sonnet Lite software. Figure 1(a) shows the schematic of the one-pixel assuming YBCO film. The total length of the rewound strip is about 12.5 mm, corresponding to the half-wavelength of the resonance frequency (5 GHz) on a MgO substrate. Each detector is connected to a coplanar waveguide with line and gap widths of 40 and 10 $\mu$m, respectively, which corresponds to the specific impedance of 50 $\Omega$ for lossless readout. The numerical simulation was conducted in the 1–10 GHz frequency range under the conditions summarized in Table 2. The parameters used were those of YBCO material properties reported by other research groups [17, 18], not the fitting vales generated from our measured resonances. The analytical model was encased in an air cubic box with each side of 5000 $\mu$m (figure 1(b)), and the upper and lower surfaces are set by free space and lossless metal, respectively, according to the actual experimental environment in our cryostat.

2.2. Simulation results

A numerical simulation was conducted by varying the $w$ and $s$ of each KID to compare the actual detectors described in the next section. In the $w$ dependence at a fixed $s = 10$ $\mu$m (figure 2(a)), the resonance frequency was obtained at 4.84, 5.19, and 5.33 GHz varying between $w = 10, 20, \text{and } 40 \mu$m, respectively. This blueshift in

| Detector type       | Noise equivalent power around liquid nitrogen temperature | Response speed (Time constant) | Array capability (Readout scheme) | References |
|---------------------|----------------------------------------------------------|-------------------------------|----------------------------------|------------|
| Kinetic inductance  | $\sim 10^{-13}$ W Hz$^{-1/2}$                            | Middle (100 $\mu$s $\sim$ 1 ms) | High (Frequency-domain)          | [10, 11]   |
| Josephson junction  | $\sim 10^{-13}$ W Hz$^{-1/2}$                            | Fast ($<100 \mu$s)             | Low (Time-domain)                | [12]       |
| Transition edge     | $\sim 10^{-13}$ W Hz$^{-1/2}$                            | Slow ($>1$ ms)                 | Low (Time-domain)                | [13]       |
frequency is regarded to be reasonable and can be explained that the inductance ($L$) decreases with an increase in $w$ under a fixed capacitance ($C$), and the resonance frequency ($f$) is inversely proportional to the square root of the inductance (i.e., $f = 1/2\pi\sqrt{LC}$). At a fixed $w = 10 \mu m$ (figure 2(b)), the resonance frequency was slightly shifted from 4.84 GHz ($s = 10 \mu m$) to 4.97 GHz ($s = 20 \mu m$) and 5.04 GHz ($s = 40 \mu m$). The relatively small shift implies that the capacitance change is less critical than the above inductance change in the spiral resonators.

The magnitude ($S_{21}$), defined as the resonance dip depth from a baseline, and the loaded quality factor ($Q_L$) as functions of $w$ and $s$ are shown in figure 3. Focusing on the $w$ dependence (along to the horizontal axis), the $S_{21}$ deepens, and $Q_L$ falls as increasing the $w$. Similarly, the $s$ dependence (along the vertical axis) also shows that the $S_{21}$ deepens and $Q_L$ falls; however, the $s$ change strongly affects the $S_{21}$ and $Q_L$ compared to the $w$ change. The $Q_L$ is related to the unloaded quality factor ($Q_U$) as $Q_U = Q_L / 10^{A_{max}/20}$, where the $A_{max}$ is the maximum attenuation at the resonance frequency, these results suggest that the narrower $w$ and $s$ are expected to have better sensitivity owing to shallower $S_{21}$ but higher $Q_L$.

### 3. Detector fabrication

YBCO thin films were deposited on MgO substrates using a reactive RF magnetron sputter equipped with a power-controlled source to verify the simulation results experimentally. KIDs were made using normal photolithography and Ar ion etching procedures on 200 nm thick YBCO films with $T_c = 84$ K. Figure 4 shows a typical detector chip with 25 rewound spirals (left) and an optical microscopy image of the one-pixel (right).
the case of \( w \) and \( s = 10 \, \mu m \), the adjacent resonator’s length differed by 30 \( \mu m \), corresponding to a designed frequency spacing of 14 MHz, this being capable of the frequency-domain multiplexing readout. 25-pixel KID arrays with two line widths (\( w = 10 \) and 40 \( \mu m \)) at a fixed \( s = 10 \, \mu m \) was prepared for the following evaluation and comparison with the above simulation.

### 4. Detector evaluation

Each KID chip was mounted into a vibration-free cryostat based on a Gifford-McMahon \(^4\)He refrigerator, as shown in figure 5. One of the scattering-matrix elements, \( S_{21} \), was measured using a vector network analyzer to determine the microwave resonance characteristics of the 25-pixel. A room temperature operated amplifier (+28 dB gain) was connected to the microwave output port of the KIDs to perform relatively low-noise measurements with low microwave power (−40 dBm).

Figure 6 shows the response of \( S_{21} \) from the 25-pixel arrays measured at an equilibrium temperature (3 K) without calibration. The 25 resonance dips for \( w = 10 \, \mu m \) were clearly observed with high uniformity in the frequency range from 5.04 to 5.42 GHz; the frequency spacing between adjacent pixels was 15.7 MHz with a standard deviation \( (\sigma) \) of 4.8 MHz. We also confirmed that the KIDs have dip depth of −9.3 dB \( (\sigma = 2.6 \, dB) \) and \( Q_L \) of 1165 \( (\sigma = 358) \) in average. For \( w = 40 \, \mu m \), the resonance dips were shifted to the higher frequency in the range of 5.59–6.37 GHz, however relatively large dispersity was observed. This is probably due to the YBCO film quality, such as the transition temperature and residual resistance, which strongly affect the resonance shape, especially for the wider \( w \) detector.

The experimental and simulation data are given in table 3, with the errors defined as the absolute values of their difference divided by the simulated values to discuss response dependency quantitatively. The first (lowest) resonance frequency \( (f_1) \), observed at 5.04 GHz for \( w = 10 \, \mu m \), was in good agreement within 4.1% accuracy.
with the simulated ones using the actual material parameters (See subsection 2.1). The ratio of the measured \( f_1 \) (1.11 times), which means the relative frequency between \( w = 10 \mu m \) and \( 40 \mu m \), was also reproduced by the simulation (1.10 times). On the contrary, relatively large discrepancies were found in \( S_{21} \) and \( Q_L \), which averaged all the resonance characteristics. The deposition of high-quality film and the optimization of photolithographic and etching processes is expected to improve the detector performance.

5. Conclusions

Predicting microwave resonance characteristics of YBCO-based KIDs with rewound strip structures is one of the essential issues for optimizing the detector performance. For this purpose, we analyzed the line-width (\( w \)) and space (\( s \)) dependence of the spiral resonators in terms of the resonance frequency, magnitude (\( S_{21} \)), and loaded quality factor (\( Q_L \)). The simulation suggested that the narrower \( w \) and \( s \) are expected to have better sensitivity due
to shallower $S_{21}$ but higher $Q_L$. Next, we fabricated YBCO–KIDs with different $w$ (10 and 40 $\mu$m) and evaluated the resonance characteristics at 3 K using a vector network analyzer. Although the $S_{21}$ and $Q_L$ have room for improvement by optimizing the YBCO film and fabrication processes, the ratio of the measured first resonance frequency (1.11 times) agreed well with the simulated ones (1.10 times).

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Seiichiro Ariyoshi https://orcid.org/0000-0001-7593-4754

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