Evaluation of YBa$_2$Cu$_3$O$_{7-8}$-based microwave kinetic inductance detectors with rewound spiral resonators

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Abstract. We propose a YBCO-based microwave kinetic inductance detector with rewound strip structure (spiral-MKID) suitable for imaging applications. The superconducting rewound strip acts as a microwave resonator and broadband antenna. A 25-pixel MKID array with a width of 10 μm and slightly varying length of each of the resonators was fabricated on a 10×10 mm$^2$-MgO substrate. Microwave resonance characteristics of the array were evaluated by measuring one of the scattering-matrix elements, $S_{11}$, using a vector network analyser. The 25 resonance dips were clearly observed around 5 GHz; the frequency spacing between adjacent pixels was 13 MHz, with a standard deviation of 5 MHz. Each resonance frequency was shifted by 170 MHz, owing to the temperature change from 11 K to 50 K. We showed that the YBCO-based spiral-MKIDs with 200 nm-thick films have loaded quality factors of 1,200 at 11 K and 700 at 50 K. We irradiated visible light to a single pixel on the array. The obtained noise equivalent power was on the order of 10$^{-9}$ W/Hz$^{1/2}$, while the response time was smaller than 30 ms at 13 K. The responsivity of the array at 70 K was six times larger than that at 13 K.

1. Introduction

Terahertz waves in the range of 0.1 THz to 10 THz are promising for applications in various non-destructive and non-invasive imaging techniques [1]. Semiconductor bolometers are commonly used as broadband terahertz-wave detectors. However, high-speed terahertz imaging arrays that have sensitivities equal to those of bolometers are not yet commercially available. Microwave kinetic inductance detector (MKID), a superconducting photon detector, is a promising candidate to achieve high-speed and high-sensitivity terahertz imaging owing to the simple fabrication of large format arrays and its frequency-domain multiplexing capability [2]. Developed MKIDs, reported by other groups, provide high sensitivity for astronomical observations; however, they utilise low transition-temperature ($T_c$) materials such as metals (Al and Nb [3, 4]) and metallic nitride (TiN, and NbN [5, 6]) superconductors, which operate at temperatures of several kelvins.

In this study, we propose an MKID array with rewound spiral resonators (spiral-MKIDs) [7, 8], using YBa$_2$Cu$_3$O$_{7-δ}$ (YBCO) thin films. The YBCO-based MKIDs do not require large and expensive cooling systems, as required for conventional MKIDs at extremely low temperatures. Therefore, they can operate using an affordable He-refrigerator or liquid nitrogen (77 K). We fabricated a 25-pixel array, which consisted of 25 rewound spiral resonators. The superconducting rewound strip acts as a high quality-factor ($Q$) microwave resonator and as a broadband antenna. It is expected that the $Q$
values are on the order of thousands at temperatures larger than 70 K. Then, we characterise and discuss the electrical and optical performances of the developed YBCO-based MKIDs.

2. Detector design and fabrication

Electromagnetic (EM) numerical simulations are a powerful tool for effective optimization of the detector design. Prior to the fabrication of the detector, we calculated the microwave properties of the MKIDs using an EM simulator Sonnet. Figure 1 shows a schematic of the spiral-MKID. The prototype array consists of a single through-line and 25 spiral resonators. Coplanar waveguide (CPW) through-line is employed for the excitation and readout. The line and gap widths of the through-line were 40 µm and 10 µm respectively, which corresponded to a specific impedance of 50 Ω. Both line and gap widths of the rewound spiral resonators were 10 µm. The resonator lengths are approximately 12 mm, designed to be consistent with the effective guided half-wavelength; the resulting resonance frequencies are expected to be about 5 GHz using an MgO substrate. The resonator lengths differed from each other by 30 µm, which corresponded to a frequency shift of approximately 14 MHz. Therefore, the array can provide frequency-domain multiplexing. A trace was introduced in each resonator circuit, adjacent to the through-line, to provide capacitive coupling. The MKID array had a two-layer structure of the YBCO film and MgO substrate; photons were directly incident on the YBCO film. This resonator geometry allows to detect broadband wavelengths, although the detectable

![Figure 1](image1.png)

Figure 1. Schematic of the spiral MKID. The inset shows magnified view around the through-line. Dark and light regions are the YBCO film and bare MgO substrate, respectively.

![Figure 2](image2.png)

Figure 2. Simulated resonant curve of the YBCO-based spiral resonator.
frequency is limited to above 7 THz, owing to the superconducting energy gap of YBCO. Figure 2 shows a simulated resonant curve of the spiral resonator. The simulation parameters were assumed to be those of a YBCO film on an MgO substrate. The sheet inductance \( (L_s) \) and sheet resistance \( (R_s) \) of the YBCO film were set to 1.0 pH/sq and \( 4.9 \times 10^{-20} \Omega \cdot \text{Hz}^{1/2} / \text{sq} \) at a temperature of 10 K, respectively [9]. MgO substrate has a thickness of 0.5 mm, a relative permittivity of about 9.7 and a loss tangent of \( 3.5 \times 10^{-6} \) was employed. For the analysis, the upper layer of the YBCO film was considered as an air with a thickness of 2.5 mm and a free space was applied as the upper boundary. The lower layer of the MgO substrate was considered as a lossless metal, which was consistent with the actual measurement environment. The calculated area was \( 5 \times 5 \text{ mm}^2 \), and the through-line and single resonator were arranged, while the length of the simulated resonator was set equal to the length of the resonator that had the lowest resonance frequency in the 25-pixel array. The simulations indicated that the resonance frequency is 4.839 GHz. Furthermore, a loaded quality factor \( (Q_L) \) of 3,800 at 10 K and a resonance dip of about 40 dB were estimated for the spiral resonator. Therefore, the YBCO-based MKID is expected to achieve high sensitivity, with \( Q_L \) smaller than that of the MKIDs based on low \( T_c \) superconductors.

Next, we deposited a 200 nm-thick YBCO film on a \( 10 \times 10 \text{ mm}^2 \)-MgO substrate using radio frequency (RF) magnetron sputtering. The YBCO thin film had a \( T_c \) of approximately 84 K. The presence of an epitaxial film was confirmed by performing X-ray diffraction analysis. Then, the YBCO-based MKID was fabricated using standard photolithography and Ar-ion etching. Figure 3 shows the YBCO-based MKID array on an MgO 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.

![Figure 3](image)

**Figure 3.** YBCO-based MKID array fabricated on an MgO substrate (left). Enlarged image of a single pixel (right).

### 3. Electrical evaluation

The fabricated chip of the YBCO-based MKID array was mounted in a cryostat (\( ^4 \text{He} \) refrigerator) and cooled down to 11 K. Microwave resonance characteristics of the array were evaluated by measuring one of the scattering-matrix elements, \( S_{21} \), using a vector network analyser (VNA). The input power of the chip was set to \(-40 \text{ dBm} \). Amplifier, which had a gain of 28 dB, operated at room temperature, was connected to the output port of the MKID array to achieve low noise measurements. This array is unaffected by the bias power of less than \(-40 \text{ dBm} \) at the through-line. At higher powers, the electric current distorted the resonance shape though non-linear effects [10]. Figure 4 shows the microwave resonance characteristics of the 25-pixel array, measured at 11 K, without calibration. A total of 25 resonance dips were clearly observed in the frequency range of 4.8 GHz to 5.2 GHz, which was in a good agreement with the simulated value (0.2 % error). The frequency interval between adjacent pixels was 13 MHz, with a standard deviation of 5.0 MHz. As shown in Figure 5 (a), the average
resonance dip had an attenuation ($A_{\text{max}}$) of 10 dB and $Q_L$ of approximately 1,200 at 11 K. The corresponding unloaded quality factor ($Q_u$) was approximately 3,000; $Q_L$ was estimated using $Q_u$ and $A_{\text{max}}$ as $Q_u = Q_L / 10^{-A_{\text{max}}/10}$ [11]. The simulated $Q_L$ and $A_{\text{max}}$ of the resonator were 3,800 and 37 dB respectively; however the measured $Q_L$ and $A_{\text{max}}$ were smaller than simulated values. It is likely that this discrepancy emerged owing to the reduced quality and surface impedance of the YBCO film. At 50 K, 23 resonance dips in the 25 resonators were identified, and the $Q_L$ was 700, while at 70 K, 13 resonance dips were identified. These resonance dips gradually disappeared at higher temperatures. The transmission of the through-line decreased to values smaller than 3 dB, at temperatures larger than 80 K. The resonance frequency was shifted by about 170 MHz by increasing the operating temperature from 11 K to 50 K.

Figure 5 (b) shows the temperature dependence of the resonance frequency. The frequency shift as a function of the temperature is:

$$\frac{\Delta f_r(T)}{f_r(T_{\text{min}})} \propto \lambda_0 \left(1 - \frac{T}{T_C}\right)^2 - \lambda(T_{\text{min}}),$$

\[(1)\]

![Figure 4. Microwave resonance characteristics of the array.](image)

![Figure 5. (a) Characteristics of the resonance dips. (b) Temperature dependence of the resonance frequency.](image)
where \( \Delta f_r(T) = f_r(T) - f_r(T_{\text{min}}) \) [12], and \( f_r, T_{\text{min}} \), and \( \lambda \) denote the resonance frequency, measured minimum temperature, and penetration depth, respectively. The penetration depth at zero temperature is \( \lambda_0 \approx 200 \) nm, obtained by extrapolation using the value at the minimum temperature. The kinetic inductance \( L_k = \mu_0 \lambda(T) \) depends on the number density of Cooper-pairs. The temperature dependence of the resonance frequency is in good agreement with the dependence obtained using Equation (1). This result suggests that the resonance frequency shift is driven by the kinetic inductance.

4. Optical evaluation

As a first step of the optical evaluation, we investigated the response of the MKID array to pulsed visible light by measuring the microwave resonance shift. The MKID array was mounted in the cryostat and cooled down to 13 K. Then, it was irradiated by white visible light (power of several microwatts) using a light-emitting diode source, while the light source was turned on at 0.5 Hz with a 50 % duty cycle. The light source was placed outside the cryostat, transformed to parallel light through an optical lens, and then irradiated to the chip through the cryostat window. The irradiated power to one pixel was estimated from directional characteristics of the light source and the area of the pixel. Since the MgO substrate has high transmittance for visible light, most of the photon absorption occurs on the YBCO film. The shift of \( |S_{21}|^2 \) was measured using a network analyser. Figure 6 shows the response to visible light observed at 13 K. Responsivity of the MKID is defined as \( d|S_{21}|^2/dP \), where

![Figure 6. Optical response of the MKID at 13 K.](image)

![Figure 7. (a) Temperature dependence of the photoresponse. (b) Frequency shift as a function of the operating temperature.](image)
d[S21]² and dP denote the response power and incident light power, respectively. The responsivity was 1.1 μW/W, while the noise power (Pn) was about 2×10⁻⁴ nW. The noise equivalent power (NEP) was defined as follows:

\[ \text{NEP} = \frac{P_n}{\sqrt{\frac{\text{d}[S_{21}]^2}{\text{d}P}}} \left( \frac{1}{W/\text{Hz}^{1/2}} \right), \]

where the frequency bandwidth (df) is defined as \( df = 1/(2\Delta f_{\text{res}}) \) [Hz]. A time interval \( \Delta f_{\text{res}} \) was approximately 0.2 ms, depending on the specification of the VNA. The resulting NEP was on the order of \( 10^{-9} \) W/Hz\(^{1/2} \) at 13 K. The obtained NEP value is limited by the fabrication process, not by the material properties. The measured response time was smaller than 30 ms. On the other hand, it was estimated that the resonator ring time \( \tau_{\text{res}} = Q_{1} / \pi f \) was on the order of microseconds [13], which is faster than the measured response time. Therefore, the measured value is thought to be due to not electric relaxation but thermal one. Optical adjustments as well as high quality YBCO film fabrication are expected to improve the performances of the detector.

We evaluated the photoresponse at higher temperatures in the range of 13-70 K, as shown in Figure 7 (a). The differential response is approximately a linear function of the incident power. The responsivity increased with the operating temperature; the responsivity at 70 K was six times larger than that at 13 K. Figure 7 (b) shows the frequency shift as a function of the operating temperature, for different values of the incident power. The frequency shift increased with the temperature. Furthermore, we observed the non-linear behaviour of the responsivity at around 70 K, which emerges owing to the large variations of \( L_{k} \) as a function of the incident power [14]. The sensitivity of the MKID depends on the \( Q \) value and frequency shift [15]. The value of \( Q \) becomes smaller at higher temperatures, while the responsivity becomes larger due to the large frequency shift. Therefore, higher sensitivity is expected by achieving good resonance properties at 77 K.

5. Conclusion
We proposed YBCO-based MKIDs with rewound strip structure suitable for imaging applications. A 25-pixel spiral MKID array with a width of 10 μm was fabricated. Its electrical and optical characteristics were evaluated. A total of 25 resonance dips were clearly observed at 11 K around 5 GHz. Each resonance frequency was shifted by about 170 MHz by increasing the temperature from 11 K to 50 K, owing to the kinetic inductance. We obtained an average \( Q_{1} \) of about 1,200 at 11 K and 700 at 50 K. Pulsed visible light was irradiated on the MKID array. The resulting NEP was approximately \( 10^{-9} \) W/Hz\(^{1/2} \), while the response time was smaller than 30 ms at 13 K. Optical adjustments and high quality YBCO-film fabrication are expected to improve the performance of the detector at higher temperatures.

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