Ultra High Q-Factor Superconducting Microresonator to Use in Microwave Kinetic Inductance Detectors

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Abstract—This article is focused on the design and development of superconducting Microwave Kinetic Inductance Detector (MKID) which is used at near, mid and far-infrared, optical and ultraviolet wavelengths for astronomical applications. MKIDs are superconducting micro-resonators which are very much considered, due to high sensitivity, simplicity in fabrication and ease of read out by a coplanar waveguide or microstrip transmission line. Here a new structure for inductor of lumped element microwave resonator is proposed that causes a very high Quality factor in smaller dimensions. Our resonator’s intrinsic Q factor is above $8 \times 10^6$ in dimensions of $441 \times 487 \, \mu m^2$ which is the highest value in such dimensions. Due to the small dimensions of this resonator, makes it desirable to use in large arrays spectrometers.

Keywords—High Quality Factor; Lumped Element Detector; Superconducting Microresonators; Microwave Kinetic Inductance Detector (MKID); Microwave Inductor Model

I. INTRODUCTION

In the last decade, low temperature detectors have been highly regarded by scientists and researchers. These detectors operate at very low temperatures even below 1 K, to have the lowest amount of noise in photon measurements and thus lead to very strong detection. Equipment based on this technology is used at millimeter and sub-millimeter wavelengths. These include Transmission Edge Sensors (TESs), Superconducting Tunnel Junction (STJ) and Microwave Kinetic Inductance Detector (MKID).

TES is a cooled particle detector and has a resistance that strongly depends on the temperature of the superconductor. By increasing the number of detectors, TESs can be multiplex in the time or frequency domains [1,2] and measurable and readable by a Superconducting Quantum Interference Device (SQUID) amplifier. But their problem in large numbers is that for a multiplexing in the time domain, we need a SQUID for each pixel and in the frequency domain, we also need a passive filter for each pixel that causes to draw a large number of wires between multiplexers and TESs. Another problem is the complexity and the heat of transmission resulting from a large multiplexed wiring array.

Another detector, STJ, consists of two layers of superconductors and a dielectric layer between them. The problem with STJ detectors is its difficult implementation [3,4] and the small size of their arrays. While for a real progress, the array should contain several thousand pixels. The technical challenge of these mentioned technologies, is the difficulty of building and reading out of their array.

MKID is a superconducting photon detector and is often developed for cosmological applications. Their advantage over other detectors is their high sensitivity, simplicity of fabrication and ease of their reading out system which can couple several thousand MKIDs only on a Coplanar Waveguide (CPW) or Microstrip transmission line.

II. THE CONCEPT OF MKID

In such detectors, photons with more energy than energy of a superconductive absorber ($E = hv > 2\Delta$) break the Cooper pairs and create quasi-particles, where $\Delta \approx 1.76 \, K_B T_c$ is the superconducting gap, $K_B$ is Boltzmann’s constant, $T_c$ is the critical temperature of the superconductor, $h$ is the Planck’s constant and $v$ is the frequency of incident photon. Photons with higher energy levels break more of the Cooper pairs. The increase in the number of quasi-particles causes the change in kinetic inductance and thus superconducting surface impedance ($Z_s = R_s + j\omega L_s$). The created quasi-particles will increase $R_s$ and $L_s$ which cause the resonance to be shifted to a lower frequency (due to $L_s$) and makes the dip wider and shallower (due to $R_s$). These effects, changes the amplitude and phase of the microwave signal coupled into the circuit, as shown in Fig. 1(a) and 1(b), respectively [5]. A method for measuring this effect and thus converting adsorbent to a detector is to integrate the adsorbent with a high quality factor superconducting resonator circuit.

Various types of MKIDs can be made. The simplest of them is the use of transmission line resonators, including CPW, microstrip, stripline and slotline. One of the microresonators that are widely used for this application are CPW quarter wave resonators [5,6]. In this case, first, the photons are absorbed by an antenna and then coupled through a transmission line to the resonator. Some of these antennas are described in [7,8]. A superconducting transmission line passes signals below the gap frequency ($f_{gap} = \Delta/h$) with the lowest losses, but the radiation above the frequency of the gap will break the Cooper pairs in the superconductor, causing a lossy transmission line. During this process, a significant amount of efficiency will be lost [9]. Some MKID’s to separate incoming signal frequencies, before the
signal is coupled to the microwave resonator, use a series of submillimeter wave superconducting resonators as a band separation filter [10,11].

Another type of microresonators, called the Lumped Element Kinetic Inductance Detector (LEKID), includes a combination of an Interdigital Capacitor (IDC) and an inductor that directly and without the need for an antenna, absorbs incident radiations. We also know that, non-linearity in superconducting devices depends on the current distribution and the geometrical structure of the device [12,13]. LEKID’s devices have a far more uniform current distribution than quarter wave resonators [14]. The inductors which have been used for these structures so far, are the Meander and Spiral [15,16,17] shown in Fig. 2.

Each of these inductors has advantages and disadvantages. For example, a resonator with meander inductor has a higher quality factor, but the resonator with spiral inductor has lower crosstalk in its array. Of course there are some ways to reduce crosstalk. Including placing the ground around the resonator, how to place the resonators in the array and etc. which are reviewed in [15].

Fig. 3(a) shows the cross sectional view of a lumped element resonator and how it absorbs radiation and 3(b) shows test setup in the laboratory. In order to better match the impedance, Titanium Nitride (TiN) film is located on a high-resistivity silicon substrate [18]. First, a millimeter or a sub-millimeter wave comes to the lens by the corrugated horn antenna. The lens concentrates the beam on the sample, then this wave passes through the substrate, which reduces its wavelength. Part of this wave is absorbed in the resonator and stimulates it and the other part that has crossed, hit with Back-shorts and return to the resonator, and absorbed to it. To have maximum absorption, we use back-short [19].

III. NEW LEKID DESIGN

The function of a KID depends extremely on the design of its resonant circuit. We proposed a new inductor structure which is a combination of a spiral and meander. Fig. 4 shows the schematic of our resonator. Our resonator made of a superconducting TiN thin film located on a silicon (Si) substrate with a dielectric constant $\epsilon_r = 11.9$ and a thickness of 150 $\mu$m. The TiN film has high kinetic inductance that reduces resonance frequency. Also, ultra-low microwave losses in this material lead to a very high Q factor [18]. According to the advantageous mentioned, we decided to use TiN film in transition temperature $T_c = 0.8$ K and the thickness of $t = 20$ nm, which has typically normal-state resistivity $\rho_n = 100$ $\mu\Omega$ cm in this circumstance. The relation $T << T_c$ is fixed; hence, we assume a value of 100 nK for working temperature $T$. To design the resonator, we must first specify the resonance frequency and then, from equation $\omega = 1 / \sqrt{LC}$ we can consider the values for the inductance and capacitance. An approximate estimation for the capacity of interdigital capacitor, obtained from the following formula [15]:

$$C = \varepsilon_0(1 + \varepsilon_r) \frac{K(k)}{K(k')^2} N_{cap} S_{cap}$$

Here, $k = \cos(\pi f_{gap} / 2)$ where $f_{gap} = g_{cap} / (g_{cap} + w_{cap})$ is gap fraction, $k' = \sqrt{1 - k^2}$ and $K(k)$ is the elliptic integral. $N_{cap}$, $S_{cap}$, $g_{cap}$ and $w_{cap}$ represent the number of IDC finger pairs, length of fingers, gap between fingers and width of fingers strip respectively. In this way, the surface inductance of $L_s$ is obtained from the general formula [20]:
Where $h = h / 2\pi$ is reduced Planck's constant and the total kinetic inductance is calculated as follows [20]:

$$L_k = L_s \left( \frac{1}{w} \right)$$  \hspace{1cm} (3)

Where $l$ is the strip length and $w$ is its width. Other design specifications for the inductor and capacitor of our resonator are given in Table I.

For our resonator we obtained $L_k = 82 \, nH$ and $C \approx 10.6 \, fF$.

In general, the dimensions of the resonator will be $441.66 \times 487.5 \, \mu m^2$. The central strip width of CPW feedline, equal to $s = 10 \, \mu m$ and the distance to the ground plane on both sides is about $g = 2s/3 \approx 6 \, \mu m$ to provide the characteristic impedance of 50 $\Omega$. The width of the ground plane around the resonators is also $80 \, \mu m$.

### Table I. Design Parameters of New LEKID

<table>
<thead>
<tr>
<th>Inductor Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The most left strip length</td>
<td>450 $\mu m$</td>
</tr>
<tr>
<td>Strip width</td>
<td>2.5 $\mu m$</td>
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<tr>
<td>Gap between strips</td>
<td>10.42 $\mu m$</td>
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<tr>
<td>Total length $\times$ width</td>
<td>452.5 $\times$ 441.66 $\mu m^2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interdigital Capacitor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip width</td>
<td>5 $\mu m$</td>
</tr>
<tr>
<td>Gap between strips</td>
<td>5 $\mu m$</td>
</tr>
<tr>
<td>First finger length</td>
<td>204.22 $\mu m$</td>
</tr>
<tr>
<td>Other finger length</td>
<td>424.16 $\mu m$</td>
</tr>
<tr>
<td>Total length $\times$ width</td>
<td>35 $\times$ 441.66 $\mu m^2$</td>
</tr>
</tbody>
</table>

Fig. 4. Schematic of proposed resonator for LEKID

Fig. 5. $S_{21}$ curves of the LEKID resonator with proposed inductor in CST and HFSS softwares

IV. Results and Discussion

After simulation the resonator in both CST Studio Suite and HFSS softwares, Fig. 5 was obtained as a result. This curve, shows that the new LEKID structure resonates at a frequency of 5.3624 GHz. 50 MHz difference in results, is due to the different analysis methods in the softwares and their accuracy in frequency sampling rate.

In fact, resonators are described by their quality factor. The Q factor is defined as [19]:

$$Q_L = \frac{1}{Q_0} + \frac{1}{Q_C}$$  \hspace{1cm} (4)

Where $Q_L$ is the loaded quality factor, i.e. it relates to when the resonator is excited by a transmission line in the circuit. $Q_0$ is the unloaded Q factor and $Q_C$ is the coupling quality factor which determines how strongly the resonator is coupled to the transmission line.

The quality factor can be extracted from the $S_{21}$ parameter of circuit. In Fig. 6, a resonance curve is shown, and Q factors are calculated as follows [19]:

$$Q_L = \frac{f_{res}}{\Delta f_L}$$  \hspace{1cm} (5)

$$Q_0 = \frac{f_{res}}{\Delta f_0}$$  \hspace{1cm} (6)

$\Delta f_0$ and $\Delta f_L$ specify the frequency range where energy reaches at least half its peak value. For a two port resonator, $S_{21,s}$ and $S_{21,0}$ are obtained as follows [19]:

$$S_{21,s} = \sqrt{\frac{1 + |S_{21,0}|^2}{2}}$$  \hspace{1cm} (7)

$$S_{21,0} = |S_{21,min}| \sqrt{\frac{2}{1 + |S_{21,min}|^2}}$$  \hspace{1cm} (8)
where $S_{21_{\text{min}}} = 6.25 \times 10^{-5}$ and $\kappa = 1.5 \times 10^{4}$. According to the above formulas, it is clear that the resonator’s quality factor we designed in CST, is equal to $2 \times 10^{6}$ which is a very high value for such circuits. Of course, in HFSS it was almost equal to $2 \times 10^{6}$ which is still a good amount.

Changes in resonator quality in terms of working temperature are shown in Fig. 7 and we see that as the temperature rises, the Q of the resonator decreases.

In Table II we have reviewed and compared other work done in the field of lumped element detectors in summary. All resonators have interdigital capacitor and their dimensions are less than 1 mm$^2$. There is only one resonator that has a Q factor of more than $1 \times 10^{7}$ [21] which, because its dimensions are 1 mm$^2$, we have avoided bringing it to the table.

In the below table, although first resonator has smaller dimensions than our, but it has a higher frequency and less Q factor. The second resonator has a lower resonance frequency than our resonator, but its size is bigger and has less Q factor. The third resonator has also a low frequency, larger dimensions and a lower resolution. Finally, the fourth resonator which is slightly larger than our resonator and works at a lower frequency, has a low quality factor.

V. Conclusion

To make a larger array of MKID’s for applications like Cosmic Microwave Background (CMB), optical astronomy and dark matter detectors, we need small resonators with a high quality factor at the resonant frequency. A new structure for LEKID was presented which showed that it could provide a very good resolution in small dimensions. The new inductor used in lumped element resonator resulted in $8.93 \times 10^{6}$ Q factor at 5.3624 GHz frequency and resonator dimensions of $441.66 \times 487.5 \mu m^2$.

### REFERENCES


### TABLE II. COMPARISON AND REVIEW THE PARAMETERS OF OTHER RESONATORS

<table>
<thead>
<tr>
<th>Number of Resonator</th>
<th>Ref.</th>
<th>Substrate Material</th>
<th>Film Material</th>
<th>Film Thickness (nm)</th>
<th>Inductor Type</th>
<th>Dimensions ($\mu m^2$)</th>
<th>Resonance Frequency (GHz)</th>
<th>Q Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[14]</td>
<td>Sapphire</td>
<td>Al</td>
<td>130</td>
<td>Meander</td>
<td>304x365</td>
<td>6.58</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>2</td>
<td>[15]</td>
<td>Si</td>
<td>TiN</td>
<td>40</td>
<td>Meander</td>
<td>935x975</td>
<td>1.5</td>
<td>$1.7 \times 10^6$</td>
</tr>
<tr>
<td>3</td>
<td>[15]</td>
<td>Si</td>
<td>TiN</td>
<td>20</td>
<td>Spiral</td>
<td>500x645</td>
<td>1.5</td>
<td>$3.8 \times 10^6$</td>
</tr>
<tr>
<td>4</td>
<td>[16]</td>
<td>Sapphire</td>
<td>NbN</td>
<td>150</td>
<td>Spiral</td>
<td>480x480</td>
<td>4.498</td>
<td>$2 \times 10^6$</td>
</tr>
<tr>
<td>5</td>
<td>This work</td>
<td>Si</td>
<td>TiN</td>
<td>20</td>
<td>Proposed inductor</td>
<td>441x487</td>
<td>5.362</td>
<td>$8.9 \times 10^6$</td>
</tr>
</tbody>
</table>


