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 8×10^6 in dimensions of 441×487 µm^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 ($E = h\nu > 2\Delta$) 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 ($V_{gap} = \Delta/h$) 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

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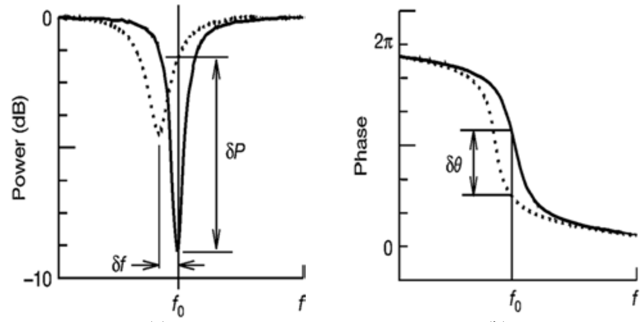
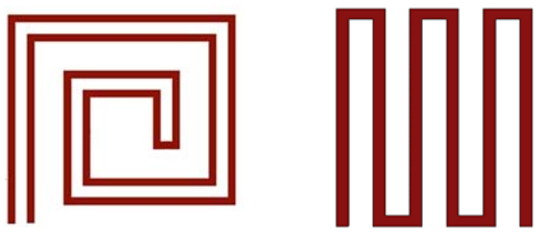


(a) (b)

Fig. 1. (a) amplitude change and frequency movement and (b) phase change in microwave signal due to increased Z_s

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.

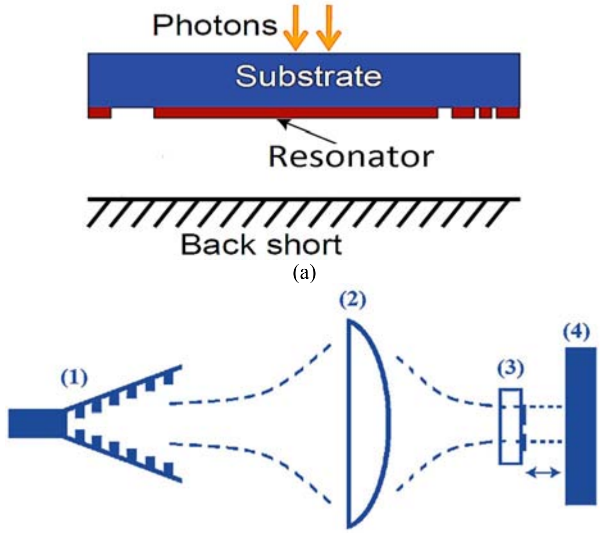


(a) (b)

Fig. 2. The (a) Spiral and (b) Meander inductors which are used in LEKID

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



(a)

(b)

Fig. 3. (a) cross sectional view of a LEKID resonator (b) setup for measuring the absorbed power by LEKID structure in laboratory. (1) Corrugated horn antenna at or below millimeter wavelengths. (2) Corrugated quasi-optical lens. (3) sample under test. (4) Back-short with variable distance to sample.

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 $\varepsilon_r = 11.9$ and a thickness of 150 µm. 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 mK 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]:

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

Here, $k = cos\ (\pi\chi_{gap} / 2)$ where $\chi_{gap} = g_{cap} / (g_{cap} + w_{cap})$ 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]:

$$L_s = \frac{\hbar}{\pi \Delta_0} \frac{\rho_n}{t} \qquad (2)$$

Where $\hbar = h / 2\pi$ is reduced planck's constant and the total kinetic inductance is calculated as follows [20]:

$$L_k = L_s \left(\frac{l}{w}\right) \qquad (3)$$

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 $L_k \approx 82\ nH$ and $C \approx 10.6\ fF$.

In general, the dimensions of the resonator will be 441.66 × 487.5 μm². 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 Ω. The width of the ground plane around the resonators is also 80 μm.

TABLE I. DESIGN PARAMETERS OF NEW LEKID

Inductor Parameters	**Value**
The most left strip length	450 μm
Strip width	2.5 μm
Gap between strips	10.42 μm
Total length × width	452.5 × 441.66 μm²
Interdigital Capacitor	**Value**
Strip width	5 μm
Gap between strips	5 μm
First finger length	204.22 μm
Other finger length	424.16 μm
Total length × width	35 × 441.66 μm²

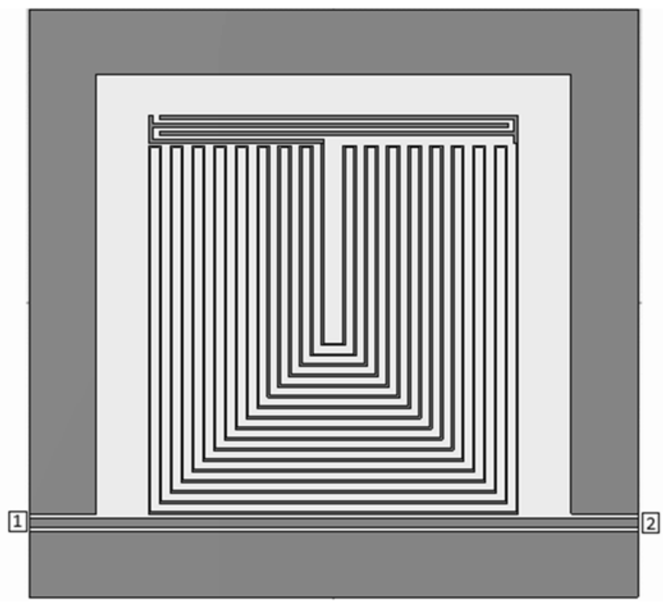


Fig. 4. Schematic of proposed resonator for LEKID

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]:

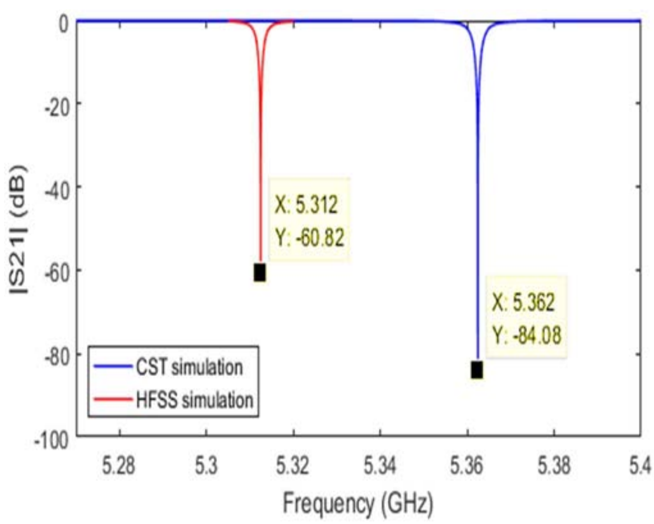


Fig. 5. S_{21} curves of the LEKID resonator with proposed inductor in CST and HFSS softwares

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

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]:

$$Q_L = \frac{f_{res}}{\Delta f_L} \qquad (5)$$

$$Q_0 = \frac{f_{res}}{\Delta f_0} \qquad (6)$$

Δf_0 and Δf_L specify the frequency range where energy reaches at least half its peak value. For a two port resonator, $S_{21,L}$, $S_{21,0}$ and Q_C are obtained as follows [19]:

$$S_{21,L} = \sqrt{\frac{1 + |S_{21min}|^2}{2}} \qquad (7)$$

$$S_{21,0} = |S_{21min}| \sqrt{\frac{2}{1 + |S_{21min}|^2}} \qquad (8)$$

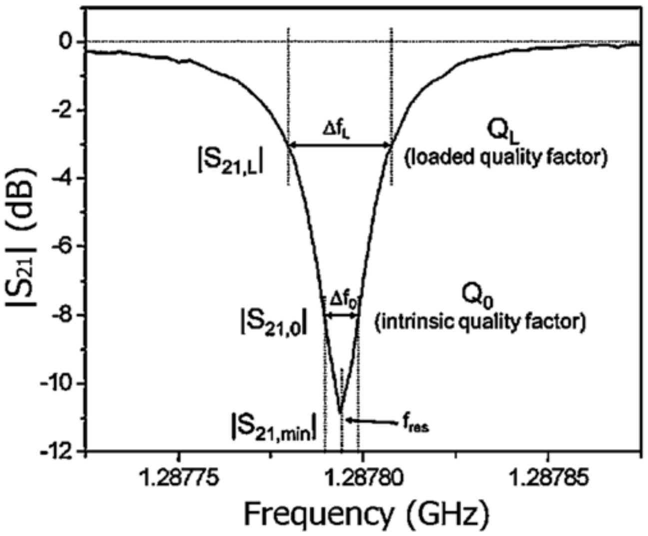


Fig. 6. The resonance curve of a resonator coupled to a transmission line

$$\kappa = \frac{1 - |S_{21,min}|}{|S_{21,min}|} \tag{9}$$

$$Q_C = \frac{Q_0}{\kappa} \tag{10}$$

Where $S_{21min} = 6.25 \times 10^{-5}$ 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 8.93×10^{6} which is a very high value for such circuits. Of course, in HFSS it was almost equal to 2×10^{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 1×10^{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

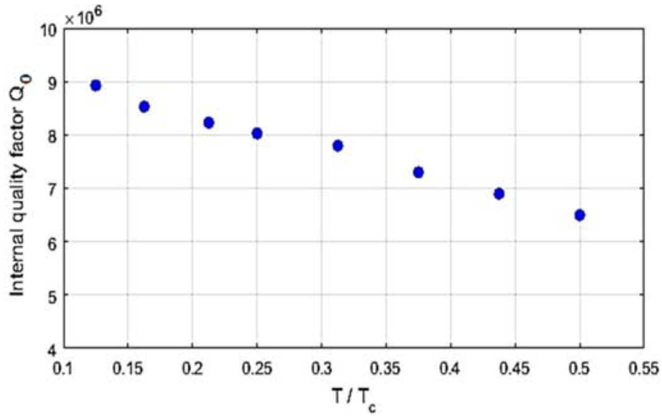


Fig. 7. Q_0 changes in terms of working temperature

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 8.93×10^{6} Q factor at 5.3624 GHz frequency and resonator dimensions of 441.66 × 487.5 μm^2.

References

[1] J. Chervenak, K. Irwin, E. Grossman, J. Martinis, C. Reintsema, and M. Huber, "Superconducting multiplexer for arrays of transition edge sensors," Applied Physics Letters., vol. 74, no. 26, pp. 4043–4045, 1999.

[2] J. Yoon, J. Clarke, J. Gildemeister, A. Lee, M. Myers, P. Richards, and J. Skidmore, "Single superconducting quantum interference device multiplexer for arrays of low-temperature sensors," Applied Physics Letters., vol. 78, no. 3, pp. 371–373, 2001.

[3] D. Twerenbold,. "Giaever–type superconducting tunneling junctions as high-resolution X–ray– detectors," Europhysics. Letter, vol. 1, no. 5, pp. 209–214, 1986.

[4] H. Kraus, F. Vonfeilitzsch, J. Jochum, R. Mossbauer, T. Peterreins, and F. Robst, "Quasiparticle trapping in a superconductive detector system

TABLE II. Compare and Review the Parameters of Other Resonators

Number of Resonator	Ref.	Substrate Material	Film Material	Film Thickness (nm)	Inductor Type	Dimensions (μm^2)	Resonance Frequency (GHz)	Q Factor
1	[14]	Sapphire	Al	130	Meander	304×365	6.58	1×10^{5}
2	[15]	Si	TiN	40	Meander	935×975	1.5	1.7×10^{6}
3	[15]	Si	TiN	20	Spiral	500×645	1.5	3.8×10^{5}
4	[16]	Sapphire	NbN	150	Spiral	480×480	4.498	2×10^{5}
5	This work	Si	TiN	20	Proposed inductor	441×487	5.362	8.9×10^{6}

exhibiting high-energy and position resolution," Physics Letters B, vol. 231, pp. 195–202, 1989.

[5] B.A. Mazin, "Microwave kinetic inductance detectors," PhD dissertation, California Institute of Technology, 2004.

[6] J. Gao, "The physics of superconducting microwave resonators," PhD dissertation, California Institute of Technology, 2008.

[7] S.M. H. Javadzadeh, "Superconducting microstrip-fed antenna; coupled to a microwave kinetic inductance detector," Journal of Communication Engineering, vol. 2, no. 4, pp. 379-389, 2013.

[8] P. K. Day, H. G. Leduc, A. Goldin, T. Vayonakis, B. A. Mazin, S. Kumar, J. Gao, J. Zmuidzinas, "Antenna-coupled microwave kinetic inductance detectors," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 559, no. 2, pp. 561-563, 2006.

[9] S. Doyle, P. Mauskopf, J. Naylon, A. Porch, and C. Duncombe. "Lumped element kinetic inductance detectors," Journal of Low Temperature Physics , vol. 151, no. 1 ,pp. 530-536, 2008.

[10] A. Endo, C. Sfiligoj, S. J. C. Yates, J. J. A. Baselmans, D. J. Thoen, S. M. H. Javadzadeh, P. P. Van der werf, A. M. Baryshev, T. M. Klapwijk, "On-chip filter bank spectroscopy at 600-700 GHz using NbTiN superconducting resonators," Applied Physics Letters, vol. 103, no. 3, p. 032601, 2013.

[11] A. Endo, J. J. A. Baselmans, P. P. Van der werf, B. Knoors, S. M. H. Javadzadeh, S. J. C. Yates, D. J. Thoen, L. Ferrari, A. M. Baryshev, Y. J. Y. Lankwarden, P. J. de Visser, R. M. J. Janssen, T. M. Klapwijk, "Development of DESHIMA: a redshift machine based on a superconducting on-chip filterbank," In Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VI, vol. 8452, p. 84520X, 2012.

[12] S. M. H. Javadzadeh, A. Bruno, F. Farzaneh, M. Fardmanesh, "Non-linearity in superconducting coplanar waveguide rectangular-spiral resonators," IET Microwave, Antenna & Propagation, vol. 9, no. 3, pp. 230-236, 2014.

[13] S. M. H. Javadzadeh, F. Farzaneh, M. Fardmanesh, "Modeling of unusual nonlinear behaviors in superconducting microstrip transmission lines," Physica C: Superconductivity, vol. 486, pp. 37-42, 2013.

[14] S. Doyle, "Lumped element kinetic inductance detectors," PhD dissertation, Cardiff University, 2008.

[15] O. Noroozian, "Superconducting microwave resonator arrays for submillimeter/far-infrared imaging. PhD dissertation," California Institute of Technology, 2012.

[16] K. Hayashi, A. Saito, Y. Ogawa, M. Murata, T. Sawada, K. Nakajima, H. Yamada, S. Ariyoshi, T. Taino, H. Tanoue, C. Otani, S. Ohshima, "Design and fabrication of microwave kinetic inductance detectors using NbN symetric spiral resonator array," Journal of Physics: Conference Series 507, vol. 507, no. 4, p. 042015, 2014.

[17] G. Jones, B.R. Johnson, M.H. Abitbol, P.A.R. Ade, S. Bryan, H.M. Cho, P. Day, D. Flanigan, K.D. Irwin, D. Li, P. Mauskopf, H. McCarrick, A. Miller, Y.R. Song, C. Tucker "High quality factor manganese-doped aluminum lumped-element kinetic inductance detectors sensetive to frequency below 100 GHz," Applied Physics Letters, vol. 110, no. 22, p. 222601, 2017.

[18] O. Noroozian, P. Day, B. H. Eom, H. Leduc, and J. Zmuidzinas, "Crosstalk reduction for superconducting microwave resonator arrays," IEEE Transactions on Microwave Theory and Techniques, vol. 60, no. 5, pp. 1235-1243, May 2012.

[19] R. Markus, Development of lumped element kinetic inductance detectors for mm-wave astronomy at IRAM 30 m telescope, KIT Scientific Publishing, vol. 12, 2014.

[20] J. Zmuidzinas, "Superconducting microresonators: physics and applications," Annual Review of Condensed Matter Physics, vol. 3, no. 1, 2012.

[21] H.G. Leduc, B. Bumble, P.K. Day, B.H. Eom, J. Gao, S. Golwala, B.A. Mazin, S. McHugh, A. Merrill, D.C. Moore, O. Noroozian, A.D. Turner, J. Zmuidzinas, "Titanium nitride films for ultrasensitive microresonator detectors," Applied Physics Letters, vol. 97, no. 10, p. 102509, 2010.