

Superconductor Microwave Kinetic Inductance Detectors: System Model of the Readout Electronics

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Abstract. *This paper deals with the readout electronics needed by superconductor Microwave Kinetic Inductance Detectors (MKIDs). MKIDs are typically implemented in the form of cryogenic-cooled high quality factor microwave resonator. The natural frequency of these resonators changes as a millimeter or sub-millimeter wave radiation impinges on the resonator itself. A quantitative system model of the readout electronics (very similar to that of a vector network analyzer) has been implemented under ADS environment and tested by several simulation experiments. The developed model is a tool to further optimize the readout electronic and to design the frequency allocation of parallel-connected MKIDs resonators. The applications of MKIDs will be in microwave and millimeter-wave radiometric imaging as well as in radio-astronomy focal plane arrays.*

Keywords

Microwave Kinetic Inductance Detectors, MKID, superconductors, microwave radiometers, radio-astronomy, radiation detector, resonators.

1. Introduction

Superconductor Microwave Kinetic Inductance Detectors (MKIDs) make use of the change in the surface impedance of a superconductor as incoming photons break up Cooper pairs. This is accomplished by making the strip of superconductor part of a microwave resonant circuit, and monitoring the phase of a signal transmitted through the resonator itself [1]. Because of their high responsivity and low Noise Equivalent Power (NEP), MKIDs have recently proposed as detectors for millimeter and sub-millimeter wave radio-astronomical observations as well as for radiometric imaging. In addition, several MKIDs could be combined to form a passive sensing array. With this approach a direct imaging will be possible by simply placing the array in the focal plane of the radio-telescope, i.e. without the need to spatially scan the main antenna of the system.

Dealing with many MKIDs (one for each pixel), however, has a main problem: a large number of coaxial cables

are needed to come in and out of a multi-stage cryostat, thus making impossible, in practice, such an approach. To solve this problem a frequency division multiplexing has been suggested. In this way only two coaxial cables (one for input and one for output) are needed, whereas each pixel is realized exploiting a MKID microwave resonator at a different frequency. Because of the very high quality factor of these superconductor resonators (typically 10^6), thousand of pixels can be allocated in a frequency band of few GHz.

The above approach is enabled by a readout electronics resembling that of a Vector Network Analyzer [2]. Purpose of this electronic is the measurement of the frequency response of the resonator, both in magnitude and phase. Since the quality-factor of the MKID resonators is very high particular attention must be paid to the stability of the frequency source. The latter is realized with high-end Phase-Locked Loop (PLL) synthesizer.

In this paper a system model of the readout electronics is proposed for the first time and implemented under ADS environment. The architecture of the system is discussed starting from that reported in [1]. First an equivalent circuit of the MKID resonator is developed. Then system-level simulations are performed showing that the readout of more resonators connected in parallel (i.e. of more pixels) is possible through a single frequency sweep.

2. System Architecture

The block diagram of the single channel is in Fig. 1. It is composed by a PLL-synthesizer acting as frequency source [3]. This synthesizer will be controlled by an external PC through a serial interface (RS-485 in Fig. 1). The main purpose of the control is to set the frequency generated by the source. This frequency should be in the range 4 GHz to 8 GHz (one octave) in such a way as to accommodate MKID resonators of different mechanical length.

In order to measure the frequency response of the resonator, the frequency must sweep between a minimum value and a maximum value. Such a frequency sweep is accomplished in discrete steps. For each step, the suitable frequency value is programmed into the synthesizer and the resonator output is measured. All these operations are controlled by the above mentioned PC.

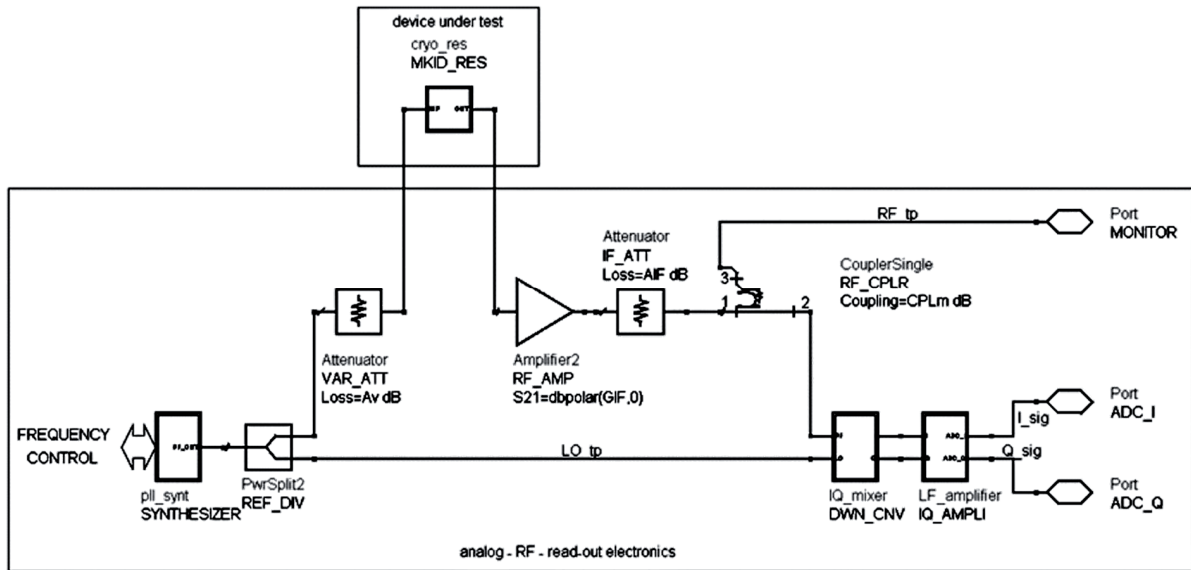


Fig. 1. Readout electronics for Microwave Kinetic Inductance Detectors: block diagram.

Once the carrier-signal at the desired frequency has been generated, it is divided in two equal parts, i.e. two signals with half of the original power and with the same phase are produced. To this purpose a broadband power divider is adopted [4]. The first output of the power divider is exploited as reference signal and is wired to the Local Oscillator (LO) input of the I/Q down-conversion mixer [5]. The second output of the power divider is first adjusted in level by an attenuator and then addressed to the cryogenic resonator.

Such a resonator constitutes the Device Under Test (DUT) of our measurement system and is interfaced with the readout electronics by means of high-quality microwave cables. At this point it is important to note that the superconductor resonator works at only 120 mK [1, p. 57] within a two-stage dilution refrigerator. In order to avoid the resonator warming (and thus the shift of its frequency) under the effect of the incident power, the resonator itself is tested at a quite low-power level (typically -96 dBm). This means that an amplifier chain is needed to improve the signal-to-noise ratio of the present measurement system. The first stage of such an amplifier is cooled down to 4 K and is placed within the first-stage of the dilution refrigerator. This amplifier features a full 4-8 GHz coverage, a power gain of 14 dB and an equivalent input noise temperature of 4 K.

The signal emerging from the DUT returns to the readout electronics to be measured both in amplitude and phase. This task is accomplished by a conventional homodyne receiver [6]. The receiver is composed by a low-noise amplifier [7] with 71 dB gain and 120 K noise temperature and by an I/Q mixer. The I/Q mixer, available as a single component, has been simulated exploiting two mixers, one which includes 90 degrees phase shift before its LO. The In-phase (I) and Quadrature (Q) outputs of the mixer are two baseband signals. The main property of the I/Q signals is that the sum of their squared values is proportional to the

squared amplitude of the incoming RF signal while the ratio between Q and I signals is proportional to the tangent of the RF signal phase.

One problem when dealing with homodyne receivers is that the relevant frequency component of the I/Q signals is the DC component. This means that unavoidable offset, gain and phase imbalance of the I/Q mixer must be removed by suitable calibration procedures. In addition, this scheme suffers of low-frequency noise (flicker noise) problems. The latter aspect must be carefully considered in selecting the low-frequency amplification circuitry. Such a circuitry can be implemented by means of low-noise operational amplifiers [8] as in Fig. 2.

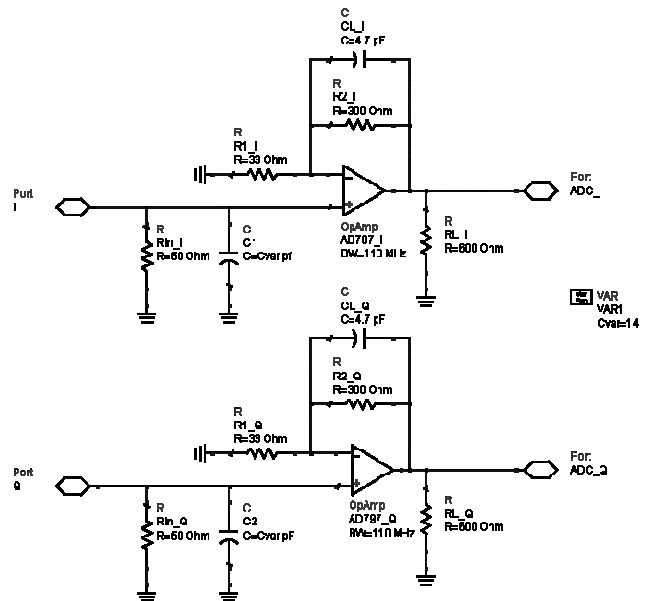


Fig. 2. Low frequency amplifier and filtering section.

The voltage gain of the operational amplifiers has been set to 10. Once amplified by the operational ampli-

ers the two channels are filtered by means of integrated continuous-time Low-Pass Filters [9]. These components are used to set the equivalent noise bandwidth, and thus the sensitivity, of the receiver. The system specifications are summarized in Tab. 1.

Minimum frequency	4GHz
Maximum frequency	8GHz
Frequency step	1kHz
Maximum quality factor	1000000
Phase noise @10kHz offset	-100dBc/Hz
Output power level	13dBm
Readout power	-96dBm
RF power @I/Q mixer input	<-10dBm
Attenuator loss	66dB
LNA gain	72dB
Mixer loss	8dB
Operational amplifier gain	10
LPF bandwidth	650kHz

Tab. 1. System specifications.

3. Resonator Modeling

The MKID resonators are implemented in coplanar waveguide (CPW) technology as reported in [1] and will not further be described here. Their equivalent circuit can be reduced to that in Fig. 3 where a quarter-wave transmission line section is coupled to the signal line by means of a small capacitor.

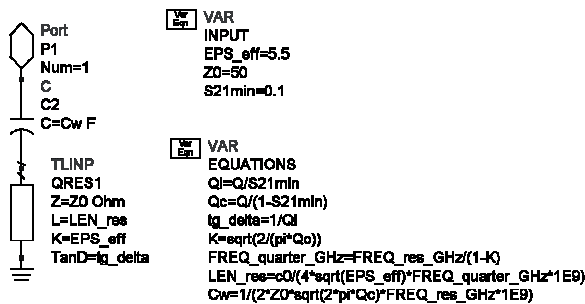


Fig. 3. MKID resonator model developed under ADS.

This model is completely defined by the following circuit parameters: physical transmission line length, effective dielectric, lossy factor and coupling capacitance. These parameters have been obtained according to the equations in [1, pp. 27-29] as a direct function of the resonance frequency, loaded quality factor and minimum value of |S21|.

To test the equivalent circuit, a 6 GHz resonator has been considered. The magnitude and phase responses are illustrated in Fig. 4. In this case the loaded quality factor is equal to 10^5 with a minimum insertion loss of -20 dB. The simulated frequency span is of only 800 kHz.

Finally, the above resonator equivalent circuit has been inserted into a system-level model of the DUT (see Fig. 5). As explained in the previous section, the DUT includes also a cryogenic low-noise amplifier. In addition a 40dB attenuator is used to set the readout power level. Such an attenuator is again within the first refrigerator

stage: as a consequence its noise temperature contribution is only 4 K.

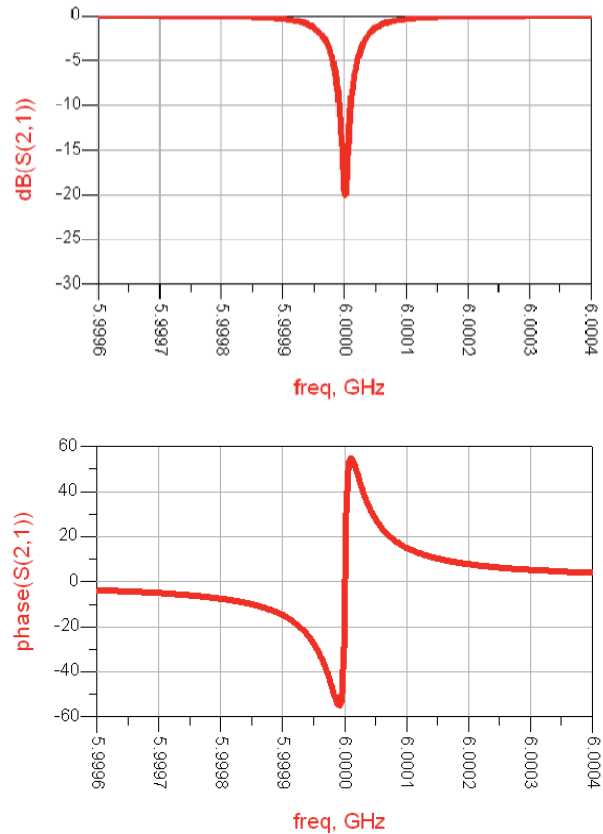


Fig. 4. Frequency response (top panel: magnitude; bottom panel: phase) of a 6GHz resonator with $Q_l=10^5$ and minimum |S21| equal to -20 dB.

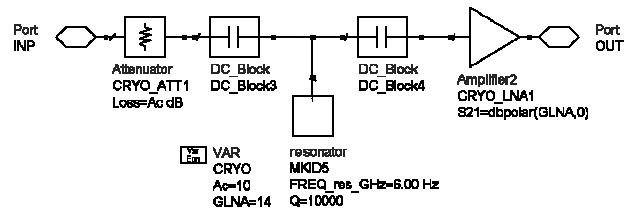


Fig. 5. System model of the DUT with attenuator, low-noise amplifier and resonator equivalent circuit.

4. System Modeling

The whole measurement system has been modeled under ADS exploiting behavioral building-blocks for all the components (i.e. mixer, power dividers, attenuators, amplifiers, etc.). Because of the I/Q mixers, a non-linear analysis has been carried-out exploiting the Harmonic Balance (HB) simulator. The purpose of this simulation is to determine the output I and Q signals (DC voltage components) when the synthesizer frequency is varied. Such a synthesizer is described with a “P_1Tone” frequency source neglecting its phase noise. The results of HB simulations are: verification of the architectural choices and check of the selected components in terms of gain, at-

tenuation and conversion loss. The HB simulation uses the MKID resonator model developed in the previous section.

The effect of the parasitic signal injection bypassing DUT is not considered in the present version on the model. This problem has been treated in [1, p. 69] where a carrier suppression mechanism is provided in the system architecture. Such a feature, however, has not been used by the author of [1] in producing the experimental results reported.

5. Results

This section describes the simulation results of the whole system. First DUT composed by a single MKID resonator with quality factor equal to 10^5 is considered. One of the most valuable results of the HB analysis is that the I/Q output signals can be evaluated versus the frequency. This means that the voltage values at the outputs of our system can be obtained while simulating a frequency sweep. Fig. 6 illustrates these results, plotting the I and Q signals over a span of 800 kHz. In Fig. 7, instead, the Q signal has been drawn versus the I signal. As a result a trajectory in the I/Q plane is obtained, very close to that reported in actual measurements, [1, p. 82].

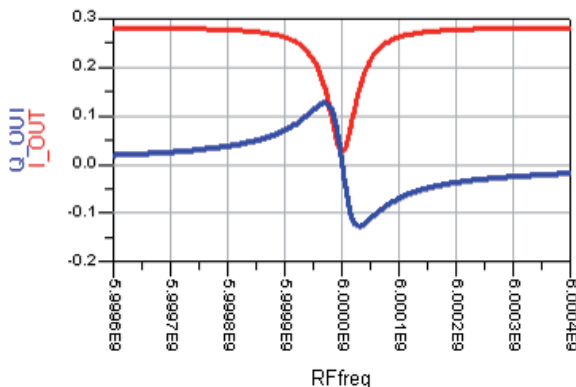


Fig. 6. I and Q voltage levels in V for a 6GHz resonator with $QI=10^5$ and minimum $|S_{21}|$ equal to -20 dB.

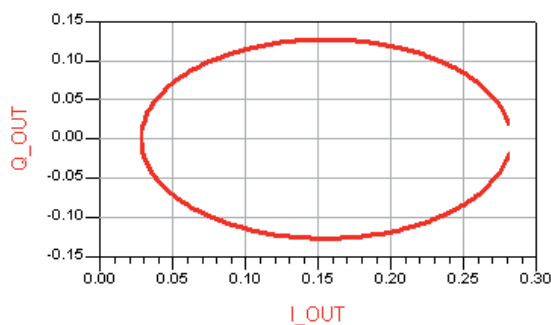


Fig. 7. I/Q trajectory for a 6GHz resonator with $QI=10^5$ and minimum $|S_{21}|$ equal to -20 dB.

The obtained voltage range of the output signals is about 300 mV: this with -10 dBm of power at the mixer input. In addition the Q signal can reverse its polarity. These details must be carefully considered when selecting the ADC and/or the data acquisition board.

In the second simulation experiment two MKID resonators with different frequencies and quality factors are electrically connected in parallel to form a multi-resonator DUT. It is worth noting here that such a possibility, although identified by [1], has never been experimented in practice. The frequencies of the two resonators are respectively 6000 MHz and 6002 MHz, whereas their quality factors are 10^4 and 10^5 .

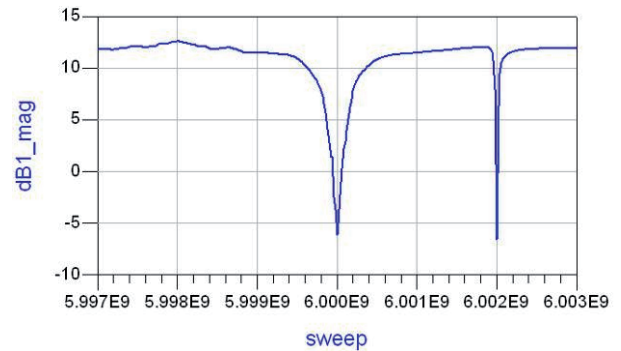


Fig. 8. Unnormalized response of two resonators in parallel, with quality factors equal to 10^4 and to 10^5 respectively. The whole frequency span is 6 MHz.

After the simulation the I and Q voltages have processed in such a way as to obtain the magnitude of the vector (i.e. square root of the sum between I^2 and Q^2) for each frequency point. This magnitude is plotted in dB without normalization. The latter normalization could be achieved considering the off resonance value or by a calibration (replacement of the DUT with a through connection). From the analysis of this figure the behavior of the two resonators is clearly visible.

6. Conclusions

The analog-RF readout electronics needed by MKID applications has been studied in depth both from the architectural and system point of view. A system model of such electronics has been proposed for the first time and developed under ADS environment. The possibility of detecting several resonators within a single frequency sweep has been investigated by means of the developed model. Exploiting this methodology a large number of resonators could be tested with only one cryostat and two coaxial cables: one for input and one for output. This solution will be particularly useful for future microwave and millimeter-wave radiometric imaging systems as well as in radio-astronomy focal plane arrays. In this framework, the developed model could be useful in determining the frequency plan of the resonators prior of their fabrication.

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Federico ALIMENTI was born in Foligno, Italy, in 1968. He received the Laurea degree (summa cum laude) and the Ph.D. degree from the University of Perugia, Italy, in 1993 and 1997 respectively, both in Electronic Engineering. In 1993 he held a scholarship from DaimlerBenz Aerospace, Ulm, Germany. In 1996 he was awarded as young scientist from URSI (Union Radio-Scientifique Internationale) and he was visiting scientist at the Lehrstuhl für Hochfrequenztechnik at the Technical University of Munich, Germany. Since 2001 he has been with the Department of Electronic and Information Engineering at the University of Perugia as a Researcher (Assistant Professor), teaching the classes of "Telecommunication Electronics". In 2006 he has been elected as a member of the University Senate of the University of Perugia. His scientific interests concern the modeling, design and characterization of microwave integrated circuits in CMOS and Si/SiGe BiCMOS technologies. Federico Alimenti is IEEE Member and has participated to the TARGET (Top Amplifier Research Group in a European Team) Network of Excellence. He has authored or co-authored more than 100 papers in international journals, conference and books chapters.

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Luca ROSELLI was born in Florence, Italy, in 1962. He received the Laurea degree from the University of Florence, Italy, in 1988. From 1988 to 1991 he worked at the University of Florence on SAW devices. In November 1991, he joined the Institute of Electronics at the University of Perugia, Italy, as a Researcher (Assistant Professor). In 1992 he became an IEEE member. Since 1994 until 1998 he had been teaching "Electronic Devices" at the same University. Since 1998 he has been teaching "Microwave Electronics" and "High Frequency Electronic Devices"; in 2007 he taught "Electronics Fundamentals". Since 1998 he was included in the TPC of the International Microwave Symposium. In June 2000 he was appointed as Associated Professor in Applied Electronics at the University of Perugia. In the same year he founded the WiS Srl and in 2005 he founded DiES Srl, two spin-off companies with which he is currently cooperating as a consultant. In 2001 he was elected "Senior Member" of IEEE society. In 2007 he organized as chairman the 7th CEM-TD Workshop (an IEEE event). In 2008 he has been appointed as director of the Science and Technology Committee of the research center "Pischiello", recently founded in Umbria, Italy, for the development of high technology in the automotive field. In 2009 he was nominated vice-chairman of the MTT-SC-24, "Radio Frequency Identification Systems". His scientific production counts more than 160 contributions to international reviews and symposium mainly concerning on the development of numerical methods for the analysis of microwave and millimeter wave electronic circuits, and for the design and development of electronic systems and sub-systems.