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Superconducting Quantum Arrays with High Spurious-Free Dynamic Range

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***Abstract*—Development of broadband superconductor sensors / amplifiers capable of providing high Spurious-Free Dynamic Range is now fairly specialized, especially in the frame of broadband receiving systems with direct digitizing. This paper is to review our theoretical and experimental results on Superconducting Quantum Arrays suggested for development of the broadband sensors / amplifiers, including active Electrically Small Antennas.**

Keywords—Josephson junctions; Superconducting Quantum Arrays; Quantum Cells; active antenna; linearity; dynamic range.

I. Introduction

Superconducting Quantum Arrays (SQA) are special arrays designed to achieve both highly linear magnetic signal to voltage transfer function and high dynamic range [1]. SQA is a uniform periodic structure composed of identical superconducting cells with a linear voltage response to applied magnetic signal. These cells are electrically connected in series or in parallel-series and can form a 1D array, a 2D array or a 3D multi-chip array. SQA is characterized by independent operation of individual cells and collective behavior of an entire array generating an output signal. The dynamic range of the linear output signal increases with the number of cells N proportionally to $\sqrt{N}$.

Integrating SQA with a broadband input microwave line or with a superconducting flux concentrator to apply an input magnetic signal to all array cells, one can design a broadband high-performance amplifier or broadband active Electrically Small Antenna (ESA) of a transformer type [1-3]. Moreover, SQA in the form of 2D array of superconducting quantum cells with nonsuperconducting electric connection of the cells can be used directly as an active ESA of a transformer-free type [1-3].

Antenna is a key element of all transmitting and receiving systems realizing wireless communications and broadcasting. The most effective antennas are usually resonant structures, resonating at the frequency of operation (e.g., [4]); their physical size is integer fractions or multiples of the wavelengths they are designed for. Among antennas in use, a considerable part is ESAs in which the maximum physical dimensions are small compared to the wavelength of interest. ESAs are not self-resonant, but made resonant by some sort of loading, commonly by using lumped elements [5], through cancelling high reactance $X_A(\Omega)$ of the antenna impedance $R_A + iX_A(\Omega)$. A high Q-factor $Q_A = X_A(\Omega)/|R_A|$ means a sharp resonance and a narrow bandwidth of ESA [5] $BW \sim 1/Q_A$.

All the appreciable improvements of the antenna's characteristics are associated with use of the active-type circuit elements. Substantial increase in the bandwidth can be obtained with use so-called non-Foster circuits [6] capable of producing negative resistance, inductance, or capacitance for the impedance transformation and matching. Next, to achieve a wideband operation, one can couple the ESA to a voltage or current broadband sensor (amplifier) whose input impedance is nearly purely reactive with same sign and frequency dependence as that of the antenna [7] or using approach suggested in [8]. Such a small antenna integrated with a sensor / amplifier is often called active ESA.

Development of the broadband active antennas is now in demand with progress in the wireless information technologies, in the first place for the broadband receiving systems with direct digitization of input signal [9-14]. The broadband reception technology becomes possible due to progress in the high-performance superconductor Analog-to-Digital Converters (ADC). The present day superconductor ADCs demonstrate both the outstanding linearity and dynamic range up to 90dB and higher [15-17]. However, the inferior linearity and dynamic range of antenna and low noise amplifier compared to those of the ADCs constrain now the overall system performance. Development of the high-efficiency active ESA capable of providing simultaneously highly linear reception and amplification with a wide dynamic range (i.e., with a high SRDR - Spurious-Free Dynamic Range) will help to overcome these limitations and improve the overall system performance. These requirements can be met with implementation of the SQA-based active ESAs.

In this paper, we review basic characteristics of the SQAs and the SQA-based active ESAs, including experimental data, specifics of use and limitations.

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II. Basic Relations

Linearity of the SQA output voltage is directly determined by the voltage response linearity of the Superconducting Quantum Cells (SQC) used as basic blocks for the SQA. Two types of the cells were proposed: bi-SQUID [18, 19] and the so-called differential cell (DQC) consisting of two differentially connected parallel arrays of Josephson junctions [20, 21]. The latter delivered better performance for SQAs. Numerical simulation shows that DQC is able to support as high linearity as 100 dB [21]

To meet requirements for both the dynamic range and impedance of the SQA, one should use a series-parallel connection of SQCs, e.g., an SQA composed of the K_P in parallel-connected blocks, each consisting of K_S serially connected SQCs. When considering the SQA with DQCs, the array structure can be presented as the one consisting of two (right and left) differentially connected shoulders, composed of right and left shoulders of DQCs respectively (see schematic in Fig. 1). In this case, the total number of cells $N = K_P K_S$ determines dynamic range of the linear output signal [1]:

$$DR = (K_S K_P)^{1/2} DR_1 \,, \tag{1}$$

while the output signal amplitude is proportional to K_S, and the SQA impedance (normal resistance R_N) is determined by ratio of the series to parallel indexes:

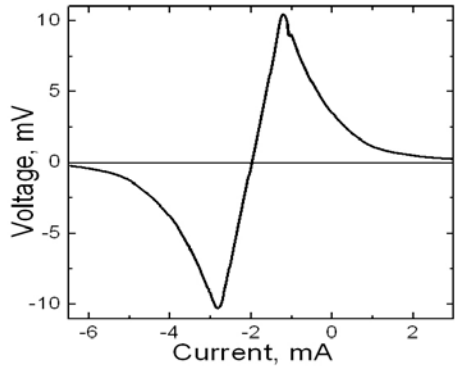
$$R_N = R_{N1} \cdot K_S / K_P \,, \tag{2}$$

where R_{N1} and DR_1 are normal resistance and dynamic range of one SQC. When writing the formulas, it has been supposed that impedance of the coupling inductances between the in parallel connected blocks is much less (at signal frequency) than normal resistance of the blocks [21].

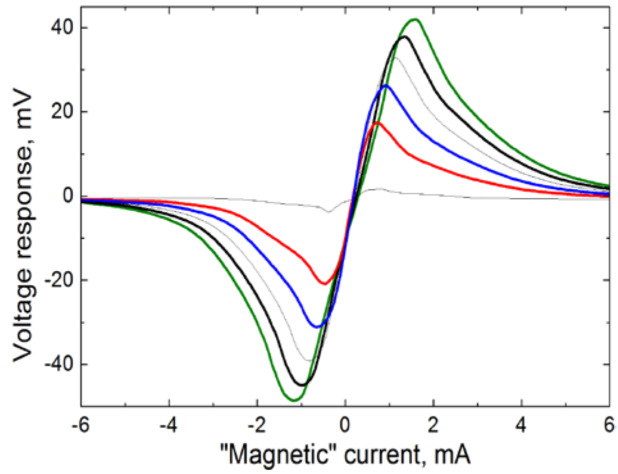
III. Limiting factors

There are two factors limiting the output signal linearity. The first one is the load connected to output of the SQA-based device. SQA is a one-port network biased by a strongly fixed optimal current. The connected in parallel load causes dynamical change in the SQA biasing. As shown in [22] for SQA composed of DQCs, the load impact can be balanced by the correction of the bias current when the load impedance R_e is higher by at least 15 to 20 times than impedance (normal resistance) of the SQA shoulder. This means that output current can reach ~5 to 7% of the bias current I_b applied to the SQA shoulders. Thus, in contrast to linear microwave networks, including passive antennas, the standard matching approach is not applicable for the active SQA-based devices. In spite of the obligatory-strong mismatching of such a device, the high output power can be achieved at the expense of power supply.

When an active SQA-based antenna is to be connected to a low-impedance superconductor ADC (usually a few Ohms), the overall performance strongly depends on the interface in use. As suggested in [23], the implementation of a broadband impedance transformer in the interface allows keeping high linearity of the SQA-based antenna output and delivering the maximum power to the superconductor ADC.



a



b

Fig. 1. (a) Adopted from [20]/ Voltage responses of 1D SQA consisting of 108 DQCs. (b) Adopted from [1]. A set of the voltage responses of the transformer-free antenna prototype containing 560 DQCs. The responses are measured at different magnetic biasing of the DQC shoulders. When testing, a magnetic field was applied using an external multi-turn coil.

For instance, when antenna impedance (2) is reduced to 2 to 3 Ohm, a 50-Ohm cable can be directly connected to the antenna output. Next, using the 50 Ohm to 5 Ohm impedance transformer, one can proceed to 5-Ohm line matched well with ADC.

Next limiting factor is as follows. When implementing the SQA-based antennas, the output signal linearity can be limited by size effects [23, 24]. The effects can be observed for some preferential direction in the transformer-free active antenna when the multi-loop and differential cells are used, as well as in the multi-loop transformer antenna with differential cells. Implementation of the single-loop transformer antenna or the transformer-free antenna with one-loop cells allows obviating the size effects.

IV. Experimental Data

Several SQAs and SQA-based ASA prototypes of both the transformer and transformer-free types were fabricated using HYPRES 4.5 kA/cm^2 niobium process [25]. The antenna prototypes occupies an area of 3.3×3.3 mm^2 on a 5×5 mm^2 chip. Fig. shows the measured voltage responses for a 1D SQA consisting of 108 DQCs [20] and a transformer free antenna prototype containing 560 DQCs [1]. The antenna circuit was designed in the form of two differentially connected arrays of the serially connected DQC shoulders. The total peak-to-peak voltage response of this antenna prototype reaches almost 100 mV, and the steepness of the magnetic signal conversion into output voltage is $dV/dB \approx 6500\ \mu V/\mu T$. When testing, a magnetic

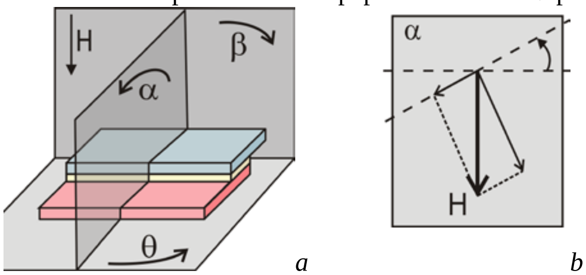


Fig. 2. (*a*) A two superconductor plate (film) model of a shoulder of DQC. The in parallel connected Josephson junctions are formed between the films in the overlapping area. α, β, and θ are angles of rotation in the planes shown. (*b*) Angle α of the directional diagram when sum of two fluxes, which are (i) transformed from perpendicular field and (ii) the directly applied to the junction array, gives peak of the diagram.

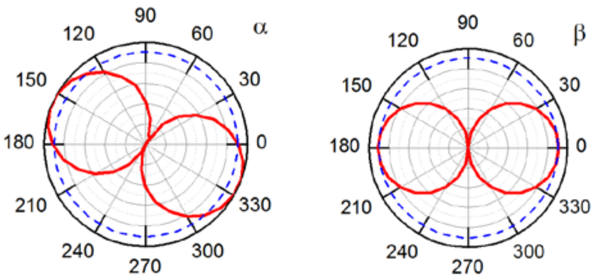


Fig. 3. Directional patterns for transformer-less ESA in two mutually perpendicular planes for the rotation angles α and β as shown in Fig. 2*a*.

field was applied using an external multi-turn coil. This setup did not allow measuring linearity of the voltage response using two-tone technique. However, evaluation of the transformer-based antenna prototype containing 80 DQCs showed linearity of about 70 dB [2]. This was measured at signal frequency 300 kHz within ~30% to ~80% of the linear region of the voltage response.

Despite the frequency limitation imposed by the measurement unit in use, the obtained characteristics can be translated quite realistically into much higher frequencies up to at least several GHz at characteristic Josephson-junction frequency ~100 GHz for the devices.

V. Discussion

Among possible SQA-based devices, the practical implementation of the active ESAs of both the transformer and transformer-free types is significantly simplified due to the absence of input microwave line. Taking into account both the basic relations and existing limiting factors, one can chose optimal type of the antenna and optimal design of the SQA and its cells to achieve an admissible tradeoff in meeting all the requirements specified.

In case of a transformer ESA, directional pattern is just the same as for usual coil ESA. To analyzer directional diagram of a transformer-less ESA composed of DQCs, we performed 3D numerical simulation of DQC under incident electromagnetic wave at frequency 1 GHz, using a simplified model.

In niobium fabrication technology, the shoulder of DQC can be modeled in the first approximation by a rectangular object of two in part overlapped superconductor films *S*1 and *S*2 as shown in Fig. 2*a*. A parallel array of Josephson junctions is formed between the films in the overlapping area. The calculated directional pattern of the cell and antenna is shown in Fig. 3. In the considered model, a total flux applied to the shoulder is a sum of two fluxes, which are (i) the transformed from perpendicular field and (ii) directly applied to the junction array (see Fig. 3*b*), therefore the pattern peaks at $\alpha \neq 0$. The shown in Fig. 3 patterns are very close to cos-dependences.

Taking into account both the basic relations and existing limiting factors, one can choose an optimal type of the antenna and optimal design of the SQA and its cells to achieve an acceptable tradeoff to meet all necessary requirements.

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