Superconducting Quantum Arrays for Broadband RF Systems

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Abstract. Superconducting Quantum Arrays (SQAs), homogenous arrays of Superconducting Quantum Cells, are developed for implementation of broadband radio frequency (RF) systems capable of providing highly linear magnetic signal to voltage transfer with high dynamic range, including active electrically small antennas (ESAs). Among the proposed quantum cells which are bi-SQUID and Differential Quantum Cell (DQC), the latter delivered better performance for SQAs. A prototype of the transformer-less active ESA based on a 2D SQA with nonsuperconducting electric connection of the DQCs was fabricated using HYPRES niobium process with critical current density 4.5 kA/cm². The measured voltage response is characterized by a peak-to-peak swing of ~100 mV and steepness of ~6500 μV/μT.

1. Introduction

A search for multi-element Josephson structures capable of providing a highly linear magnetic signal to voltage transfer with high dynamic range lead to development of Superconducting Quantum Arrays (SQAs). SQA is a homogeneous array of unique superconducting cells with a highly linear voltage response to magnetic field - Superconducting Quantum Cells (SQCs). Such an array is characterized by independent operation of the cells collectively forming a high linearity output signal. By increasing the number of the cells, \(N\), one achieves the increase in dynamic range as a square root of \(N\). This is true for both serial and parallel connections of the cells. In fact, spectral density of the low-frequency (at signal frequency) noise voltage \(S_V(0)\) across the \(N\) serially connected SQCs is \(N \cdot S_V(0)\), where \(S_V(0)\) is the one across single SQC, and therefore the mean-square-root noise voltage across the array \(V_F = [N \cdot S_V(0) \Delta F]^{1/2}\) (\(\Delta F\) is an output frequency band) increases with \(N\) as \(N^{1/2}\), while transfer factor \(K = \frac{dV}{d\Phi}\) and output signal \(V\) both increase as \(N\). At parallel connection, the transfer factor does not change, and spectral density of the low-frequency noise current \(S_I(0)\) through the parallel array is \(N \cdot S_A(0)\), where \(S_A(0)\) is the one for fluctuation-current source connected to each SQC in accordance with Langevin method [1]-[3], and therefore the mean-square-root noise voltage across the parallel array \(V_F = [N \cdot S_V(0) \Delta F]^{1/2} R_d N\) decreases with \(N\) as \(1/N^{1/2}\) (here \(R_d\) is differential resistance of a single SQC). In both cases, the reduced-to-input mean-square-root noise \(V_F/K\) determining minimum input signal decreases with \(N\) as \(N^{1/2}\).

One can design a high-performance broadband amplifier by integrating SQA with a broadband input line to apply an input magnetic signal to all array cells (see, for example, the designs proposed in [4-6]).
implement simultaneously broadband reception and amplification of electromagnetic signals. Practical implementation of these active ESAs can be significantly simplified with absence of input RF line.

2. SQA as an active electrically small antenna

There are two possible approaches to design the SQA-based active electrically small antenna (ESA). The first one is based on integration of SQA with a superconducting flux transformer (concentrator) [7, 8]. Such antenna prototypes based on a 1D array of about 80 cells were designed and experimentally evaluated [8]. With circuit area of 3.3 x 3.3 mm$^2$, the devices were characterized by transfer factor of $\sim 750 \mu V/\mu T$ and peak-to-peak linear response of $\sim 8mV$.

According to the second approach, the SQAs in form of 2D arrays of superconducting cells with nonsuperconducting electric connection of the cells can be used directly as active ESAs of a transformer-less type. Figure 1 shows schematically such a 2D SQA in an external magnetic field. Meissner effect is shown for only one row of the superconducting quantum cells (SQCs). Two types of quantum cells with linear voltage response to magnetic signal were proposed as a basic block for SQAs - SQCs: (i) bi-SQUID [9-11] and (ii) the so-called differential cell [12-14]. The latter delivered better performance for SQAs.

Differential Quantum Cell (DQC) consists of two elementary parallel arrays of $K = 10$ to 15 Josephson junctions, differentially connected and oppositely biased by some magnetic flux $\delta \Phi$. Such an implementation exploits a close-to-parabolic form of the main peak sides $V_R(\Phi)$ and $V_L(\Phi)$ of the parallel array voltage response. As long as subtraction of two identical parabolic functions with the mutually shifted vertex positions results in a linear dependence, the differential connection of two parallel arrays oppositely biased by a certain magnetic flux $\delta \Phi$ results in a circuit linear voltage response. An accurate analysis of the parallel array is a complex numerical problem. Therefore in many cases, one has to consider the array in the limit of zero coupling inductances between Josephson junctions in order to use an analytic formula to calculate a voltage response to magnetic flux.

Our detailed numerical analysis of the realistic DQC based on two parallel arrays with non-zero coupling inductances confirms its capability of providing highly linear voltage response at low, but practical normalized coupling inductances between Josephson junctions $l \sim 0.3$ to 0.7 (here $l = 2\pi I_c l/\Phi_0$, and $I_c$ is Josephson-junction critical current) [13, 14].

The array uniformity ensures a uniform distribution of the magnetic component of electromagnetic wave in the array and, therefore, provides an identical magnetic signal at the input of each SQC (maybe, except for the periphery rows, which can be excluded from the output signal formation). Figure 2 schematically shows a mechanism of conversion of the perpendicular magnetic flux applied to the entire area of the superconducting shoulder of DQC into a parallel magnetic flux applied to an elementary parallel circuit. Screening Meissner currents flow through the edges of the superconducting films $S1$ and $S2$, which form the cell, and connect over the inner surfaces of these films in the region of their overlap (where Josephson junctions are formed), and thus induce a magnetic flux to be applied to a parallel circuit of Josephson junctions. In fact, magnetic field $B$ in the gap between the superconductor films satisfies Maxwell’s equation $\text{rot}(\mathbf{B}) = \mu_0 \mathbf{j}$, and hence $B = \mu_0 j_0 \lambda$, where $j_0$ is the current density at the film surface and $\lambda$ is the magnetic penetration depth. Therefore, magnetic flux applied to every section of the Josephson-junction array equals to $B (d+2\lambda) dx =$
\[ \mu_0 j_0 (d + 2\lambda) dx, \] where \( d \) is thickness of an isolator film, and \( dx \) is a distance between Josephson junctions.

Figure 3 presents the measured voltage response of the transformer-less antenna prototype based on SQA consisting of 560 DQC and occupying area of 3.3 x 3.3 mm\(^2\). The device was fabricated using HYPRES niobium process with critical current density 4.5 kA/cm\(^2\) and Josephson-junction critical current \( I_c = 125 \mu A \) [15]. All cells of the SQA are sectioned into two serial arrays of cell shoulders (twelve-junction parallel arrays). Insets in figure 3 show typical traces of the voltage responses of the two arrays. The arrays are differentially connected to the antenna output. To realize an opposite dc magnetic flux biasing of the arrays, each array is equipped with a control line with normal-metal sections between the array elements. An external multi-turn coil was used to apply magnetic field to the antenna prototype. The total peak-to-peak voltage response of this antenna reaches almost 100 mV, and the steepness of the magnetic signal conversion into output voltage is \( dV/dB \approx 6500 \mu V/\mu T \). Our experimental setup was not designed for a two-tone technique to measure linearity of the antenna voltage response. However, our prior testing of the transformer-based antenna prototype based on DQC type cells showed linearity of about 70 dB [8]. This was measured at signal frequency 300 kHz within ~30% to ~80% of the linear region of the voltage response.

3. Conclusion
Superconducting Quantum Arrays (SQAs) can be used as front-end circuits for broadband radio frequency systems capable of providing highly linear magnetic signal to voltage transformation with high dynamic range, e.g., as active electrically small antennas. We believe that the design of an active antenna using the transformer-less antenna based on 2D SQA with nonsuperconducting electric connection of the quantum cells can lead to the most efficient design. This design allows a significant increase in a number of integrated quantum cells in fixed antenna area. Among the proposed quantum cells such as bi-SQUID and Differential Quantum Cell (DQC), the latter delivered the better performance for SQAs. The transformer-less antenna prototype containing 560 DQCs with nonsuperconducting cell-to-cell connections was realized using HYPRES niobium process with
critical current density $4.5 \text{kA/cm}^2$. The peak-to-peak voltage response of this antenna reaches almost 100 mV, and the steepness of the magnetic signal conversion into output voltage is $dV/dB \approx 6500 \mu \text{V}/\mu \text{T}$. To meet matching requirement and increase load capability, a parallel connection of the 2D SQAs can be used. Such superconducting devices can be used in broadband receiving systems with direct digitization of input signal [16-24] for communications, radar, and signal intelligence. The SQAs are also beneficial for many applications, in which SQUIDs and SQUID arrays are used [25-27].

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