High-Frequency Study of Compact Planar Capacitances in Niobium Technology

Renat Yusupov
Laboratory of superconducting devices for signal detection and processing
Kotel'nikov Institute of Radio Engineering and Electronics RAS
Moscow, Russia,
yusupovrenat@hitech.cplire.ru

Lyudmila Filippenko
Laboratory of superconducting devices for signal detection and processing
Kotel'nikov Institute of Radio Engineering and Electronics RAS
Moscow, Russia,
valery@hitech.cplire.ru

Valery Koshelets
Laboratory of superconducting devices for signal detection and processing
Kotel'nikov Institute of Radio Engineering and Electronics RAS
Moscow, Russia,
valery@hitech.cplire.ru

2023 Radiation and Scattering of Electromagnetic Waves (RSEMW) | 979-8-3503-2237-8/23/$31.00 ©2023 IEEE | DOI: 10.1109/RSEMW58451.2023.10202097

***Abstract*— A microwave method for measuring the electrical parameters of circuits, including capacitances, using superconducting resonators was proposed and implemented. An original technology of manufacturing compact capacitors in superconducting circuits with a thin anodized insulator layer was used. The structures comprising arrays of such superconducting resonators were fabricated and their spectra were measured. The numerical calculations of the test structures were compared with the spectra measured in the experiment. The values of the capacitance, through which the resonators were coupled to a microwave transmission line, were determined. The obtained values were analyzed, and the reliability of the technique used was assessed.**

Keywords— superconducting resonator, quarter-wave resonator, coplanar waveguide (CPW) line, superconducting integrated circuit, planar capacitance, anodized layer.

I. Introduction

At the present time, the development of quantum superconducting devices is showing great progress. One of the main options for the implementation of such devices are integrated circuits based on the niobium Josephson junctions [1]. In addition to the Josephson junctions and resistive shunts, the capacitive and inductive elements are used in such circuits. The challenging task is to accurately fabricate the compact elements of such circuits with the given parameters. Despite the fact that most of these elements are well calculable analytically, the parameters of the manufactured elements may differ from the calculated ones, and thus require experimental determination. For example, in the circuit of a Josephson traveling-wave parametric amplifier (JTWPA) [2], knowing of the cell-inductance and the cell-capacitance values is important, because among other things, they determine the line impedance. Previous studies [3] had shown that the indirect determination of the inductive parameters of the JTWPA in dc measurements is not ~~a~~ sufficiently reliable and accurate method. In this paper, we discuss and use an alternative scheme for measuring parameters using a coplanar waveguide (CPW) capacitively loaded with the element under study, i.e., the high-Q CPW resonator which makes it possible to determine the necessary parameters at the operating frequencies.

This research was funded by the Russian Science Foundation, grant number 21-42-04421. https://rscf.ru/project/21-42-04421/

II. Method for Determining Parameters Using a Superconducting Resonator

Thin-film superconducting coplanar waveguide resonators are widely used in the superconducting qubit circuits [4], in the matrices of bolometric receivers [5, 6], and in the material analysis systems [7,8]. There are two main ways of coupling a CPW resonator and a CPW line: capacitive [9] and inductive [10]. The design of capacitive coupling is usually more compact and thus favorable when several resonators are connected to one line. Traditionally, the capacitive-coupling design implies the gap or finger capacitors. In circuits with two or more metal layers, it is also possible to use planar capacitors, which may provide significantly larger capacitances and, consequently, a stronger coupling with the line.

The scheme for measuring inductive and capacitive elements is shown in figure 1. The frequency ω_1 of grounded, i.e. $\lambda/4$-resonator is calculated with high accuracy analytically or using microwave device simulation systems, for example, AWR Microwave Office. Terminating the similar resonator by an inductance L or a capacitance C_0 leads to a shift of the resonant frequency, down ($\omega_2 < \omega_1$) or up ($\omega_3 > \omega_1$) from the bare frequency, respectively. This shift is also calculated analytically and makes it possible to determine the load impedance value.

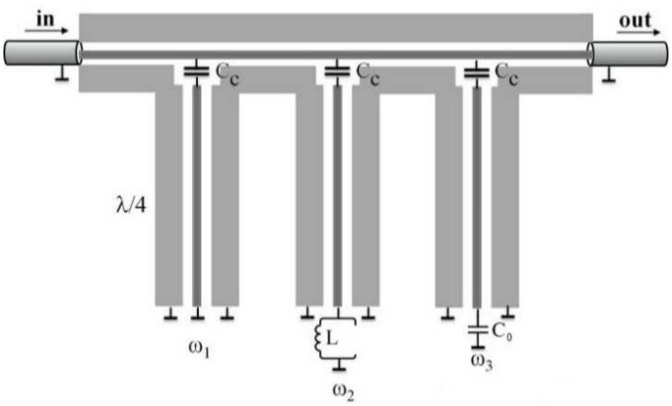

Fig. 1. Scheme of coupling coplanar waveguide quarter-wave resonators with different termination to a coplanar microwave line.

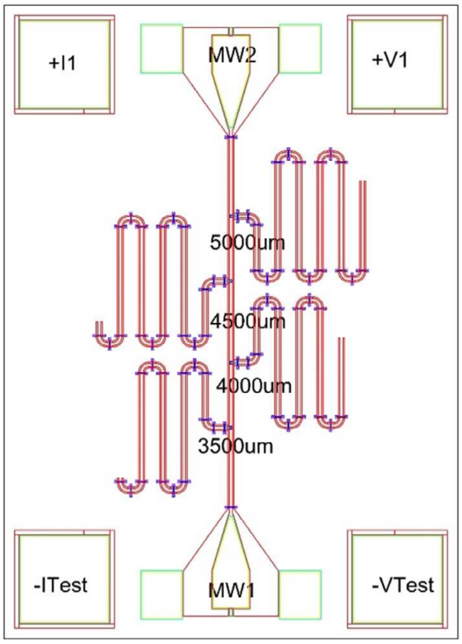

Fig. 2. The layout of the chip with 4 CPW quarter-wave resonators of various lengths capacitively coupled to a CPW line 2500 µm long. CPW is 20 µm wide and 10 µm gap. The design value of the CPW impedance is 48 Ω.

For initial research, a chip with a segment of a CPW line, and 4 CPW resonators of various lengths (3500, 4000, 4500 and 5000 µm) was developed (see Fig. 2). All CPW resonators were on one side shorted to ground and on the opposite side coupled to line capacitively at regular intervals. The coupling capacitances were 200 fF for all CPW resonators. The designed parameters ensured sufficiently pronounced (< -20 dB) high-Q (Q ~ 15) resonances. The calculation of the entire circuit was carried out in AWR Microwave Office (see Fig. 3). Resonances were at frequencies of 5, 5.46, 6.02, 6.68 GHz.

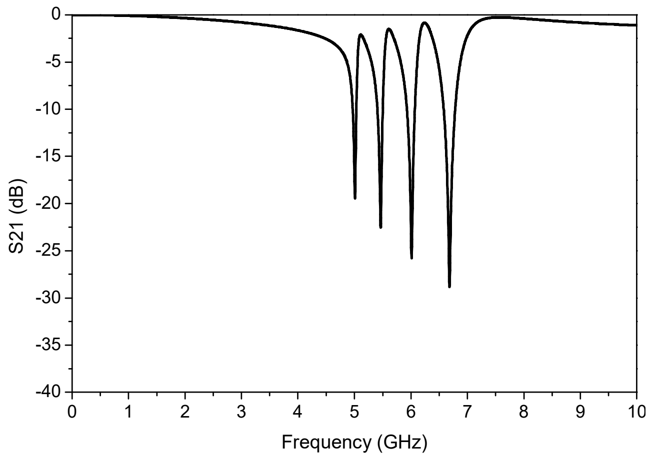

Fig. 3. Calculation in AWR Microwave Office of a signal passing through a CPW line with 4 CPW resonators coupled through identical capacitances of C_c=200 fF, on a silicon substrate (ε=11.9) with a thickness of 500 µm with a metallic layer on the reverse side (coplanar waveguide with ground).

III. Experimental Sample with Capacitors with a Thin Anodized Insulator Layer

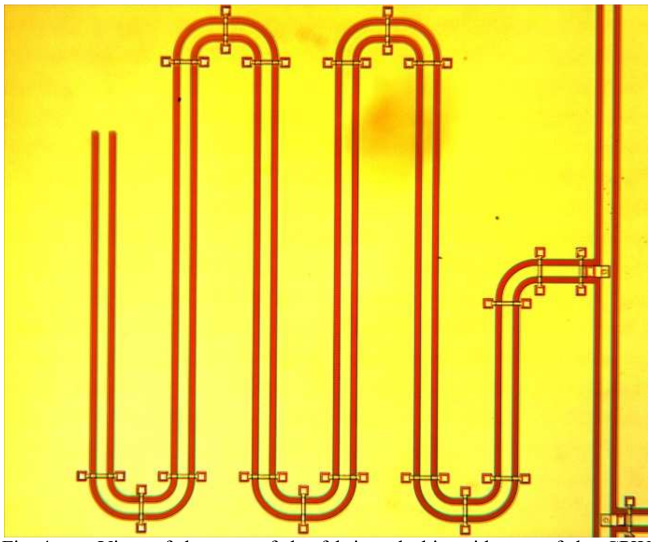

Fig. 4. View of the area of the fabricated chip with one of the CPW quarter-wave resonators capacitively coupled to a CPW line with "air" bridges.

According to the developed design, the test circuits were fabricated at the IRE RAS using niobium technology [11]. The films were deposited by magnetron sputtering, the layer structure was created using the lift-off method. The lower metal layer, in which CPW lines were made, was a three-layer structure Nb/Al-AlO_x/Nb with a thickness of 200/7/80 nm. The top layer of metal Nb of thickness of 350 nm was used to connect resonators to the line and "air" bridges, equalizing the electric potentials of the CPW line in the places of its bend. (see Fig. 4). The lower and upper layers are separated by a SiO_2 insulator layer 250 nm thick.

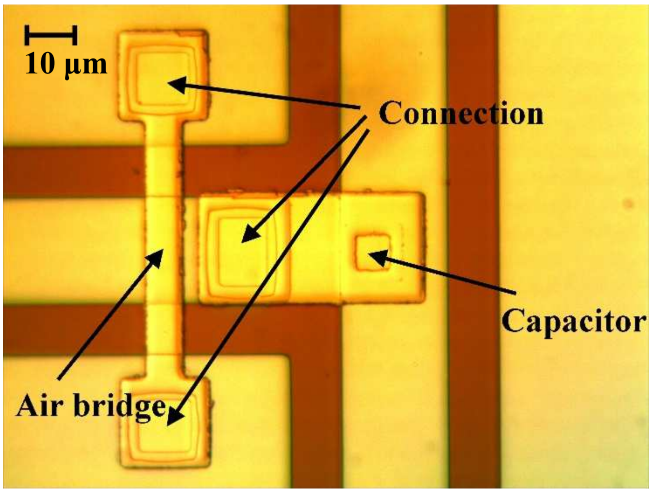

Fig. 5. Fragment of the capacitive coupling region of the CPW line and resonator. The capacitor~~,~~ area is about 6 µm by 6 µm. An “air” bridge is located on the left side, which provides electrical contact return conductors for equalizing the potentials of the line. “Air” bridge’s width is 6 µm.

TABLE I. CAPACITOR STRUCTURE

	Material	*Thickness h, nm*	*Dielectric constant ε*	*Capacitance, fF/ µm²*
M2	Nb	350	Top metal	
Ianod_1	Al_2O_3	12	10	7.4
Ianod_2	Nb_2O_5	19	40	19.6
M1	Nb	200	Bottom metal	

An original technology for manufacturing capacitors was used to couple the resonators to the line. Previously, plane-parallel capacitors with a SiO_2 insulator layer [12] separating the upper and lower metal layers were used. The specific capacitance with a 250 nm thick interlayer is 0.17 fF/µm². Also, the qubit circuits [13] use similar capacitors with a layer of amorphous silicon (a-Si), which has a dielectric constant of about 10, that is larger than that of SiO_2. In these samples, the dielectric layer was obtained by anodizing Al and Nb layers. Previously, it was proposed to use this method for shunting Josephson junctions [14]. To do this, after the formation of the topology of the lower electrode, a photo resist mask is formed, in the window of which the upper Nb layer is first etched (the Al layer is the etch stop layer). Further in this window, anodization is carried out to a voltage of 17 V. Al layer is anodized firstly: it takes of about 9 V to completely anodize Al layer and gives about 10-12 nm of Al_2O_3 layer with ε=10. Only after that the Nb layer starts, the additional anodic layer Nb_2O_5 (h = 18-19 nm, ε = 35-45) is created for the extra 8 V. As a result, we got 2 capacitors one on the top of another; total capacitance is about 5.4 fF/µm² (Table 1). At the next stage, the areas not protected by the resist mask are etched and a layer of thick SiO_2 insulator is formed, which determines the area of the final capacitor. The area, where contact with the top electrode is made, remains open. In the developed design, this area is 6 µm by 6 µm, the estimated capacitance is $C_c \approx 200$ fF (see Fig. 5).

Using the proposed technology, it is possible to manufacture the compact capacitors with a high specific capacitance, what is important for increasing the density of elements in the integrated superconducting circuits and creating compact multi-element circuits. Reducing the size of the capacitors in such circuits makes it possible to reduce parasitic size effects, hampering operation of such circuits at high frequencies.

IV. EXPEREMENT

The fabricated structures were measured at a cryogenic temperature of 4.2 K in a special probe-insert put into a transport helium Dewar vessel. The sample was bonded to a printed circuit board, where the microwave signal propagates along a microstrip line. The measuring head with the board was connected to the probe insert via SMP connectors (see Fig. 6). Additional filters and attenuators in the microwave path were not used. The measurements were carried out with a Rohde&Schwarz ZNB20 vector network analyzer at frequencies up to 20 GHz. Previously, there was a study of a signal transmission through a similar segment of a CPW line, which showed that there were no significant attenuations and reflections in the path.

Fig. 6. Photo of the measuring head with the sample connected to the cryogenic insert and the magnetic shield.

The transmission of the signal through the developed structure with resonators at a temperature of 4.2 K was measured in band 100 MHz – 20 GHz. A spectrum showed 3 high-Q resonances at frequencies of 3.9, 4.2, and 4.6 GHz and one resonance feature, at a frequency of 6 GHz (see Fig. 7). The absence of fourth high-Q resonance (the resonator with a length of 3500 µm) can be explained by the presence of a defect, i.e. a short circuit inside the resonator, shifting this resonance to higher frequencies. This resonance was excluded from further analysis.

V. RESULTS AND DISCUSSION

A more complex model is required to correctly compare the calculations with the experimental results. First of all, parasitic capacitance of "air" bridges was added to the model. Despite the low specific capacitance of 0.17 fF/ µm² of such overlaps, due to the large area, the capacitance of each bridge is estimated at 20 fF. On the longest resonator there are 18 "air" bridges in groups of 3. They are introduced into the model in groups of 3 and with a capacity of 60 fF in design-advising places. With this correction, we determine the values of coupling capacitance C_c. To match the calculation with the experiment, this capacitance should be about 375 fF (Fig. 7), that is larger than coupling capacitance used in preliminary evaluation.

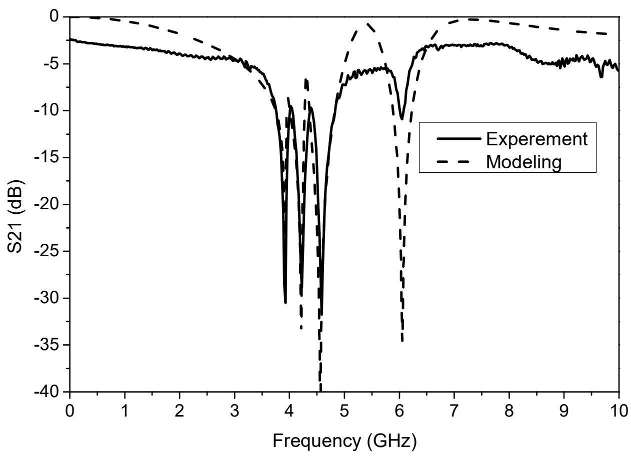

Fig. 7. Experimentally investigated signal propagation along a coplanar line and numerical calculation taking into account the capacitance of the bridges and the selected value of C_c=375 fF.

There are two main factors, that were not taken into account earlier. The first problem is related to determining the exact area of such a capacitor. In the course of manufacturing, the possibility of drifts of linear dimensions, associated with the development of the resist and the features of the formation of structures. Measurements in an optical microscope showed that the actual side size of a square capacitor was 6.7±0.1 μm.~~,~~ giving the total area of about 45 μm^2.The second problem is related to the parasitic capacitance (0.17 fF/ μm^2) of the resonator's overlap with the center line. This overlapping 275 μm^2 gives extra capacitance 47 fF, connected in parallel. That is, the capacitance of the capacitor itself is 328 fF.

The capacitance of such a capacitor amounted to 7.3±0.22 fF/ μm^2. What differs from the calculated specific capacitance according to the formula for a plane-parallel capacitor, but this estimate was made "from below". The determining factor is the thickness of the Al layer, which determines the thickness of Al_2O_3 and Nb_2O_5, which is determined in technology with an accuracy of ±10%. We associate additional corrections with the imperfection of the boundaries of such a capacitor. It is possible to refine the specific capacitance values in the experiment by comparing the frequencies of an unloaded resonator and one loaded with a large-area capacitor made according to the described technology (see Fig. 1).

The conducted research has shown that the designed and manufactured resonators are suitable for research to determine the inductive and capacitive parameters of circuit elements with a fairly simple measurement scheme. The capacitances under study ensured sufficient coupling of the resonators with the coplanar line and thus a high signal-to-noise ratio. A method was tested for manufacturing compact containers with a dielectric layer obtained by anodizing. The proposed method makes it possible to create compact planar capacitors in superconducting niobium circuits with a high specific capacitance.

Acknowledgment

The authors are grateful to Alexander Zorin for the idea of such measurements and discussion of this work. The equipment of USU "Cryointegral" was used to carry out the research; USU is supported by a grant from the Ministry of Science and Higher Education of the Russian Federation, agreement No. 075-15-2021-667.

References

[1] R. Kleiner, D. Koelle, F. Ludwig and J. Clarke, "Superconducting quantum interference devices: State of the art and applications," Proceedings of the IEEE, vol. 92, no. 10, pp. 1534-1548, Oct. 2004, doi: 10.1109/JPROC.2004.833655.

[2] A. B. Zorin, "Josephson traveling-wave parametric amplifier with three-wave mixing." Physical Review Applied vol.6, no. 3, pp. 034006, 2016. doi:10.1103/PhysRevApplied.6.034006.

[3] R. A. Yusupov, et al. "Experimental Study of Elements of a Josephson Traveling-Wave Parametric Amplifier on SQUID Chains". Phys. Solid State, 2023. doi:10.1134/S1063783422090086.

[4] A. Blais, et al. "Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation." Physical Review A, vol. 69, no. 6, pp. 062320, 2004. doi:10.1103/PhysRevA.69.062320.

[5] P. K. Day, et al. "A broadband superconducting detector suitable for use in large arrays." Nature, vol. 425, no. 6960, pp. 817-821, 2003. doi: 10.1038/nature02037.

[6] M. A. Tarasov, et al. "SINIS bolometer with microwave readout." Physics of the Solid State, vol. 62, pp. 1580-1584, 2020. doi: 10.1134/S1063783420090292.

[7] W. Rauch, et al. "Microwave properties of YBa2Cu3O7− x thin films studied with coplanar transmission line resonators." Journal of applied Physics vol. 73, no. 4, pp. 1866-1872, 1993. doi: 10.1063/1.353173.

[8] R. Barends, et al. "Contribution of dielectrics to frequency and noise of NbTiN superconducting resonators." Applied Physics Letters, vol. 92, no. 22, pp. 223502, 2008. doi: 10.1063/1.2937837.

[9] M. Göppl, et al. "Coplanar waveguide resonators for circuit quantum electrodynamics." Journal of Applied Physics, vol. 104, no.11, pp. 113904, 2008. doi:10.1063/1.3010859.

[10] D. Bothner, et al. "Inductively coupled superconducting half wavelength resonators as persistent current traps for ultracold atoms." New Journal of Physics vol. 15, no. 9, pp. 093024, 2013. doi: 10.1088/1367-2630/15/9/093024.

[11] P. N. Dmitriev, et al., "High quality Nb-based tunnel junctions for high frequency and digital applications", IEEE Transactions on Applied Superconductivity, vol. 13, no. 2, pp. 107-110, June 2003, doi: 10.1109/TASC.2003.813657.

[12] R. A. Yusupov et al., "Flux-Pumped Josephson Travelling-Wave Parametric Amplifiers Based on Bi-SQUID Cells", IEEE Transactions on Applied Superconductivity, vol.32 no. 4, pp. 1700105, 2022, doi: 10.1109/TASC.2021.3131134.

[13] J.M. Martinis, "Superconducting phase qubits", Quantum Inf Process vol. 8, pp. 81–103, 2009, doi:10.1007/s11128-009-0105-1.

[14] S. Butz, et al., "Protecting SQUID metamaterials against stray magnetic field" Supercond. Sci. Technol., vol. 26, pp. 094003(4pp), 2013, doi:10.1088/0953-2048/26/9/094003.