Spectral Characterization of Planar Resonators by Terahertz Josephson Spectroscopy

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***Abstract*—Here, we report the results of spectral analysis of planar open ring resonators by Josephson spectroscopy. Square shape resonators on separate wafers were positioned in the vicinity of $YBa_2Cu_3O_{7-x}$ bicrystal Josephson junction (JJ). The DC characteristics of JJ demonstrated specific features related to resonant modes excitation. Resonators of various sizes were analyzed, and excitation of *LC*-modes at frequencies from 50 GHz to 700 GHz were observed. Resonator quality factors were estimated using resistively shunted model of JJ and resonator equivalent circuit.**

I. INTRODUCTION

THE spectral analysis in terahertz frequency range is still challenge. Significant progress in submillimeter technology of integrated circuits requires new methods for frequency characterization of active and passive components. Network analyzers designed for that run into difficulties at frequencies above 100 GHz. recently a new method was proposed, which is based on the usage of Josephson junction (JJ) [1] for frequencies up to 1.2 THz. In this report, we demonstrate spectral characterization of passive microwave components, like open ring planar resonators, by Josephson spectroscopy.

II. JOSEPHSON SPECTROSCOPY

It is known that Josephson junction is very sensitive to its electrodynamic environment. The dc *IV*-curve of Josephson junction is modified under the influence of this environment. Using resistively-shunted junction (RSJ) model [2] such influence can be considered by a frequency-dependent complex admittance $Y_e(f)$ connected to the JJ in parallel. It was shown the change of the *I-V* curve $\delta V(I)$, measured at current bias *I*, can be described as [3]:

$$\delta V(I) = R_n (IR_n - V)\,\mathrm{Re}\left[Y_e(f)\right] \qquad (1)$$

where $V = R_n\sqrt{I^2 - I_c^2}$ is the unperturbed voltage, which is proportional to the Josephson frequency *f* as $V=hf/2e$, I_c is the critical current and R_n is the normal state resistance of the JJ. Following expression (1) the JJ converts the frequency domain into the voltage domain. Therefore external frequency-dependent admittance $Y_e(f)$ can be reconstructed from modified *IV*-curve of the JJ. In practice investigation of differential resistance vs. voltage dependence $R_d(V)$ is more suitable. Since (1) was derived in *RSJ*-model, neglecting thermal fluctuations of normal quasiparticles, accurate results for actual admittance $Y_e(f)$ can't be obtained from this expression. To take into account the influence of thermal fluctuations we used extended *RSJ*-model [1], where the JJ is presented as element with superconducting and normal currents; external structure is presented as a set *RLC*-circuits; and there are sources of thermal fluctuation currents. Spectral characterization of external structure can be carried out by fitting of simulation $R_d(V)$ curve to measured one.

III. EXPERIMENTAL DETAILS

We fabricated Josephson junctions with growth of epitaxial $YBa_2Cu_3O_{7-x}$ thin films on bicrystal MgO and $NdGaO_3$ substrates with R_n=0.3 – 50 Ohm and characteristic voltage $V_c=I_cR_n$ = 0.3 – 3 mV at T=5 K. It was shown, that such high-T_c bictrystal Josephson junctions are described by *RSJ*-model with high accuracy [4].

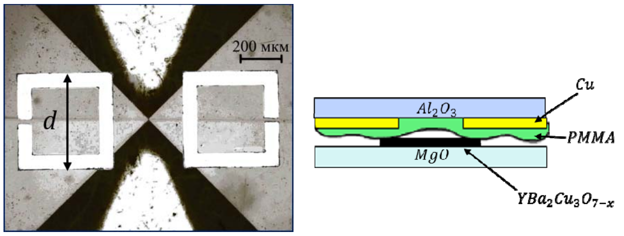

Fig. 1. Josephson junction with open-ring resonator (a), schematic layers arrangement.

Open ring planar resonators of square shape were formed from 300 nm cooper films on sapphire substrates by UV-lithography. Square side had dimensions from 30 µm to 500 µm. The resonators were covered by PMMA to prevent ohmic contact with the JJ [5]-[6].

The resonators were mechanically attached to the junction close to weak link. Relative position between resonators and JJ is shown in Fig.1. Coupling capacitances occurring in the areas of resonators and JJ overlap provide excitation of resonance modes in resonators by Josephson oscillations. The junction with resonators was mounted on cryogenic dipstick and placed into liquid-helium dewar. The dc *IV* and $R_d(V)$ – curves were measured at temperature range from 5 to 90 K. The value of V_c could be varied with external magnetic field up to 100 G.

IV. RESULTS AND DISCUSSIONS

A set of JJ $R_d(V)$ curves corresponding interaction with resonators of various dimensions is presented in Fig.2. Sharp features corresponds to excitation of resonance modes in resonators at voltage related to *f* by Josephson relation *f=2eV/h* Feature voltages are scaled with corresponding resonator side length. For observation of sharp features it is necessary to provide optimal coupling of resonator with JJ at resonance frequency which is achieved by tuning a value of

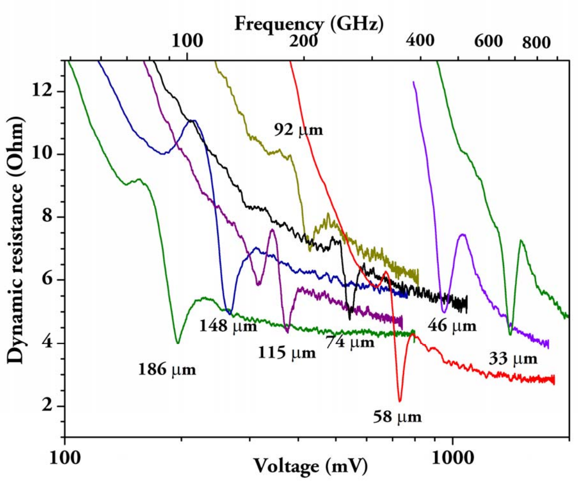

Fig. 2. Set of $R_d(V)$ curves of Josephson junction interacting with open ring resonators of various dimensions.

V_c by external magnetic field.

Using Josephson junctions on MgO and $NdGaO_3$ substrates there were observed resonance features on $R_d(V)$ curves at frequencies from 50 GHz to 700 GHz (Fig.2 and Fig.3) Parameters of resonator (resonance frequency f_r and quality factor Q) were obtained from fitting the results of numerical simulation to the results of $R_d(V)$ measurement (Fig.3). Additional JJ parameters (I_c and R_n) needed for simulation were obtained from the measured *IV*-curve. For the resonator with side length d=366 µm it was obtained f_r=48.7 and Q=20. The highest resonance frequency f_r=679.5 GHz was obtained for the resonators with d=33 µm.

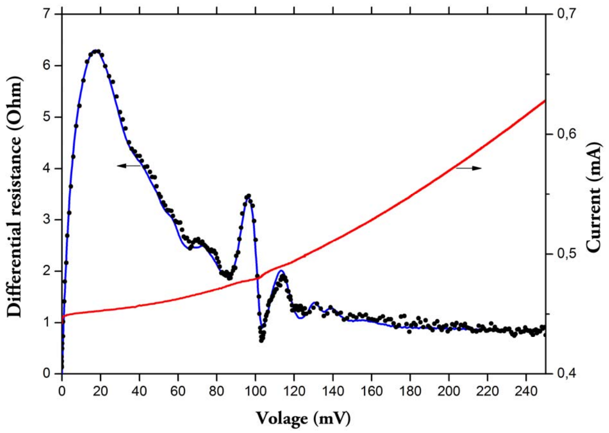

Fig. 3. The dc *IV* and $R_d(V)$ curves of Josephson junction interacting with 366 µm side length open ring resonators. Dotted line — measured data, solid line — the results of numerical simulation.

Excitation of fundamental resonance (*LC*) mode in open ring resonator corresponds to condition $l=\lambda/2$, where l – physical length of resonator, λ – wavelength of resonance mode [7]. Then:

$$f_r = \frac{c}{2l\sqrt{\varepsilon_{\text{eff}}}} \tag{2}$$

where ε_{eff} – effective dielectric permittivity of resonator environment, c – the speed of light. Since substrate (MgO or $NdGaO_3$) of JJ is enough far to resonator (by our estimates it's about some tens of µm), contribution ε_{MgO} is negligible. Then $0.5\left(\varepsilon_{\text{Al}_2\text{O}_3}+\varepsilon_{\text{PMMA}}\right)=6.7$; $l=2(d_{\text{ext}}+d_{\text{int}})$, where d_{ext}=366 µm – external size of resonator side and d_{int}=254 µm – internal size. Difference in 4 % between calculation and measured resonance frequency can be explained by influence of MgO substrate and inaccuracy of resonator physical length estimation. Calculation of the current density distribution was performed by ADS Momentum (Keysight Technologies, Inc.) simulation package for this resonator and the results are shown in Fig.4. According to [7] this current distribution corresponds to *LC*-mode excitation.

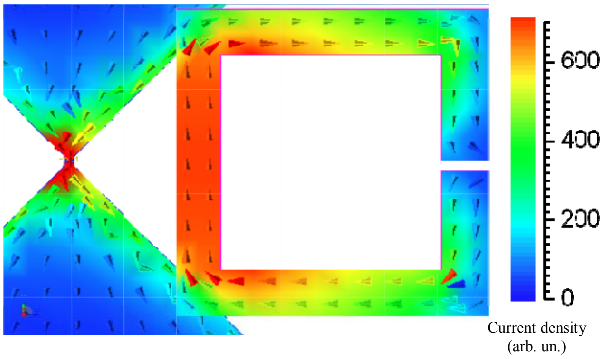

Fig. 4. Simulation with ADS Momentum (Keysight Technologies, Inc.). Current density distribution in resonator excited by Josephson junction at resonance frequency.

V. CONCLUSION

Application of Josephson spectroscopy for frequency characterization of open ring planar resonators was demonstrated. Excitation of fundamental resonance modes in resonators of various dimensions was observed at frequency from 50 GHz to 700 GHz. Using extended RSJ-model there were obtained resonance frequency f_r= 48.72 GHz and quality factor Q=20 for 366 µm side length resonator with numerical simulation.

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