Frequency Characterization of Planar Resonators by THz Josephson Spectroscopy

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Abstract— Broadband electromagnetic measurement at frequencies above 100 GHz is still challenging problem because of limited frequency ranges of oscillators, complicated matching networks and ambiguous deembedding procedures. It is known that Josephson junction (JJ) is very sensitive to electromagnetic environment. Josephson terahertz spectroscopy is based on ac Josephson effect in high-temperature superconducting junctions. Here we extend this method to perform spectral characterization of planar open ring resonators on separate substrates. We have studied resonator characteristics at frequencies from 50 GHz to 700 GHz, using $YBa_2Cu_3O_{7-x}$ high-T_c bicrystal grain boundary junctions on $NdGaO_3$ and MgO substrates. Differential resistance vs. voltage curves modified by the interaction of JJ with resonator have been analyzed. An excitation of fundamental resonance mode in the planar resonator by Josephson oscillations was demonstrated. The technique developed might be used for frequency characterization of THz photonic elements and structures.

1. INTRODUCTION

In recent years, significant efforts have been made towards development of microelectronic devices for submillimeter wave applications. Recently it was demonstrated InP high electric mobility transistor based amplifiers operating at frequencies up to 1.3 THz [1]. However, measurement and characterization of submillimeter wavelength integrated circuits and their active and passive components have always been a challenge, Network analyzers that can continuously vary the operating frequency from 40 kHz to 125 GHz are conventionally used for characterization of on-wafer planar components. Modern devices based on semiconductor frequency multipliers can increase their operating frequency up to 1 THz; however, they have narrow range of continuously tunable frequencies, which hampers their wide application. Moreover, at frequencies above 100 GHz, there are some difficulties in ensuring electromagnetic coupling of submillimeter and micron scale devices under test with the external network analyzer. This coupling is provided with the help of numerous waveguide sections and special high-frequency microprobes. Actually, measurements are performed at the external inputs of waveguides, and special deembedding procedures are used to extract parameters of the device under test [2]. These procedures include calibration measurements with the use of special calibration standards and data processing, which decreases the accuracy of the results obtained. As a result, recently, a number of on-chip characterization methods have been proposed, which should overcome drawbacks of commonly used measurement techniques. In these methods, the high-frequency part of the measurement device is integrated with the device under test on the same wafer. The main problem in realization of this method is to develop on-chip oscillator with rather high frequency. The usage of superconducting Josephson oscillator may have an advantage over other methods especially for characterization of low-temperature devices.

Few decades ago it was shown, that Josephson junction (JJ) is very sensitive to its electrodynamic environment. When Josephson junction is placed into a substance with the dispersion or attached to lamped elements with frequency-dependent characteristics, Josephson oscillations waveform is modified. This affects the dc IV-curve of the junction. It was shown that JJ can be used at the millimeter-wave wavelength range for indication of characteristic frequencies of a Fabry-Perot resonator [3], resonances in LC-circuits and coaxial lines, attached to the junction and absorption spectral lines of various substances, deposited on the weak link [4, 5]. In modern JJ, based on high-Tc superconductors (HTSC), oscillations were observed at frequencies up to 5 THz. It was demonstrated applications of HTSC JJ for frequency characterization of microstrip transmission line resonator [6] and planar antenna structures [7–9] integrated with JJ on the same wafer in frequency range from 60 to 1100 GHz. In this article we demonstrate the technique for spectral characterization of planar open-ring resonators with the usage of JJ on separate wafer.

2. THE INFLUENCE OF EXTERNAL ELECTRODYNAMIC ENVIRONMENT ON JOSEPHSON JUNCTION

It is known that dc characteristics of JJ are modified under the influence of electromagnetic environment, This modification may be caused by a variety of physical mechanisms, e.g., electromagnetic losses in materials of JJ and substrate, the influence of absorptive environment, antenna or other electromagnetic structures. In resistively-shunted junction (RSJ) model [10] the effect of all these mechanisms on JJ can be considered by a frequency-dependent complex admittance $Y_{ext}(f)$, connected to the junction in parallel. It was shown in [11] that in the case of weak binding of JJ with the environment, a deviation $\delta V(I)$ of the IV-curve, measured at current bias I, can be described by following equation:

$$\delta V(I) = R_n(IR_n - V)\mathrm{Re}\{Y_{ext}(2eV/h)\} \tag{1}$$

where $V = R_n\sqrt{I^2 - I_c^2}$ is the unperturbed voltage at the given current I, 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 JJ. The expression (1) performs mapping of frequency domain into voltage domain by Josephson relation $f = 2eV/h$. Therefore frequency dependent admittance of the external electrodynamic system can be reconstructed from dc characteristics of JJ. In practice to examine spectral characteristics of external circuits it is more suitable to measure differential resistance vs. voltage dependence $R_d(V)$ of JJ interacting with them.

The expression (1) was obtained for the general form of $Y_{ext}(f)$ in RS) model, neglecting thermal fluctuations of normal currents. At finite temperatures, monochromatic spectra of Josephson oscillations are broadened by thermal fluctuations, which significantly modify characteristic features on the IV-curves, related to external resonances. Due to this broadening, Josephson spectral analysis can be carried out at frequencies above a low-frequency limit, determined by thermal fluctuations [9]. To provide spectral analysis of electromagnetic structures at frequencies not far above this limit, a modification of IV-curves and $R_d(V)$-dependencies by thermal fluctuations should be taken into account, even at low temperatures.

Characteristics of high-T_c bicrystal junctions are described by the RSJ model with high accuracy, which simplifies the analysis. To take into account the influence of thermal fluctuations, we used an equivalent circuit of a Josephson junction with resonant electrodynamic structure, shown in Fig. 1.

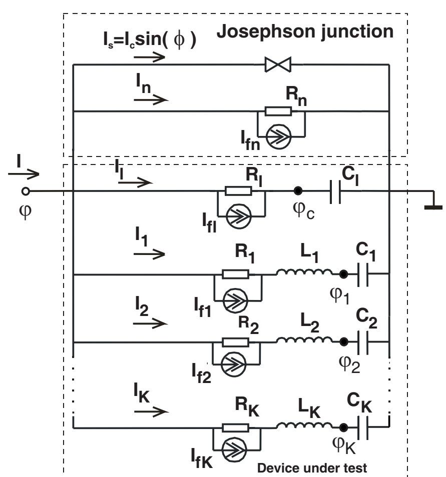
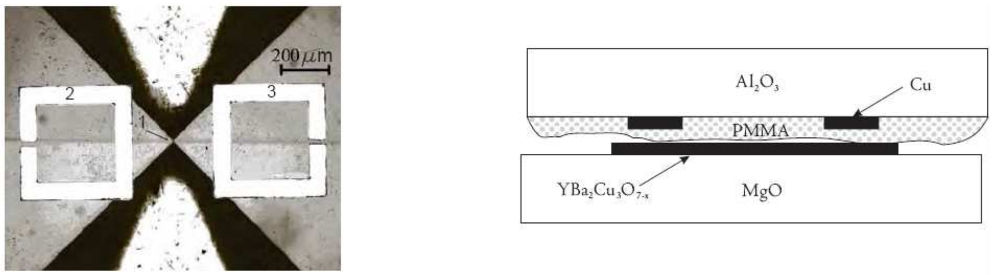


Figure 1: Equivalent circuit of Josephson junction with external electrodynamic system.

According to RSJ model, a Josephson junction is presented as an element with superconducting I_s and normal I_n currents. External structure is approximated by a set of RLC circuits. An averaged influence of the structure, which is not taken into account in the resonance circuits, and other electromagnetic environment of the junction in a broad frequency range is taken into account by R_lC_l circuit, connected in parallel to the junction. Each resistor in the equivalent circuit is considered as a source of thermal fluctuation currents I_f, approximated by white noise. DC characteristics of JJ (IV-curve and voltage dependence of differential resistance $R_d(V)$) can be obtained from numerical solution of the equation set, related to the equivalent circuit. Spectral analysis of external system can be performed by fitting of calculated JJ dc characteristics to measured ones [8].

3. DETAILS OF THE EXPERIMENT

We used a grain boundary JJ to probe a Al_2O_3/Cu/PMMA planar resonator. JJs were formed from epitaxial (001) $YBa_2Cu_3O_{7-x}$ thin films of 250 nm thickness deposited on the bicrystal MgO (ϵ=9.5) and $NdGaO_3$ (ϵ=22) substrates where ϵ is dielectric permittivity. Resonators had square shapes with side dimensions varied from 30 µm to 400 µm. They were formed from the cooper film of 300 nm thickness on sapphire substrate with ϵ=10.7 and were covered by PMMA with $\epsilon = 2.5$. Resonators were attached to JJ and were positioned in the vicinity of weak link as it shown at Figs. 2(a), (b). Resonator and JJ interlayer distance has not been controlled in our experiment (this is shown by rough line in Fig. 2(b), and may be up to few tens of microns.



(a) (b)

Figure 2: (a) Josephson junction 1 with open ring resonators 2,3. (b) Layers arrangement.

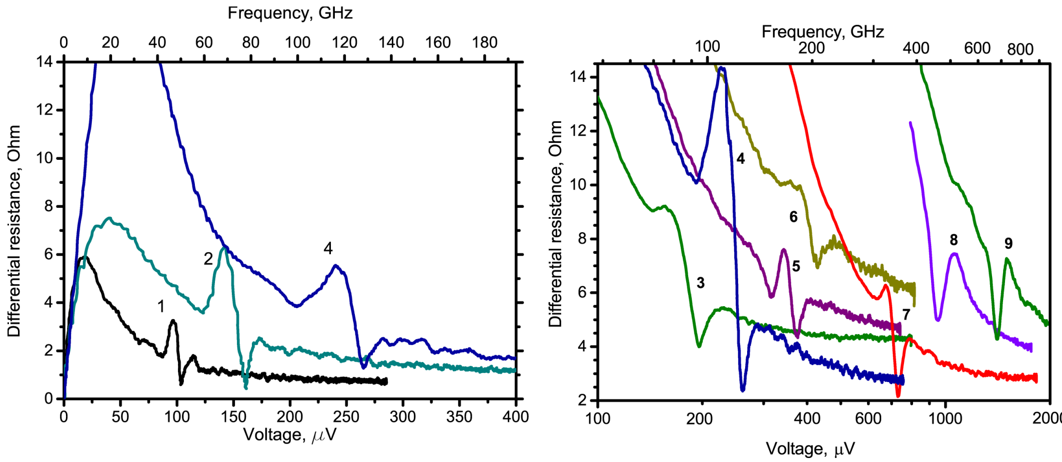
PMMA layer prevented ohmic contact between resonator and JJ. Excitation of resonators were performed by the Josephson oscillations throw the capacitance between resonators and triangle-shaped superconducting leads. Geometry of JJ leads provides a smooth impedance vs. frequency dependence, as well as sharp features at the spectral characteristic are related to interaction with resonant structure. The junction with resonators attached was mounted on a cryogenic dipstick and was placed into a liquid-helium dewar. The IV-curves and $R_d(V)$ were measured at the temperature range from 5 to 90 K. A coupling of JJ with resonator at various frequencies is determined by JJ differential resistance which depends on JJ characteristic voltage $V_c = I_c R_n$. To cover wide frequency range we used two types of JJ: JJ on MgO substrate with $V_c = 0.8\,\mathrm{mV}$ and JJ on $NdGaO_3$ substrate with $V_c = 3\,\mathrm{mV}$ at $T = 5\,\mathrm{K}$. In addition, V_c was varied by external magnetic field up to 100 G.

4. RESULTS AND DISCUSSION

$R_d(V)$ of JJ attached to resonators of various dimensions are presented at Fig. 3. Excitations of the resonators manifest themselves as sharp features at voltages, which are scaled with resonator side length. To obtain each curve V_c was tuned by magnetic field to obtain optimal coupling at resonance frequency.

Resonance features were observed at frequencies from 50 to 120 GHz on MgO based JJ characteristics and from 80 to 700 GHz on $NdGaO_3$ based JJ characteristics. A feature related to 125 GHz resonance frequency of 148 µm size resonator was observed in characteristics of both resonators at 248 µV (curve 4 at Fig. 3(a)) and 257 µV (curve 4 at Fig. 3(b)). This small difference (3.5%) indicates that JJ substrate permittivity has a minor influence on resonance frequency which can be explained by rather large interlayer distance between resonator and JJ (more than 30 µm according to estimations).

Resonant frequencies and other parameters of resonators were obtained from the analysis of measurement data based on resistively shunted model of JJ and equivalent circuit (Fig. 1) of JJ interacting with the resonator [8]. Main RSJ parameters (I_c and R_n) were obtained from measured JJ IV-curve, as well as LC-circuit parameters were obtained by fitting calculated $R_d(V)$ dependence to measured one. The results for 233 µm size resonator are presented at Fig 4. It was obtained that calculated curve corresponds to excitation of a resonator with resonance $f_r = 74.9\,\mathrm{GHz}$ and quality factor $Q = 25$. If we assume excitation of fundamental resonance mode (LC-mode) then physical length of the resonator should be equal to half-guided-wavelength $\lambda_r/2$ [12]. Therefore an effective permittivity of resonator environment ϵ_{eff} can be estimated: $\epsilon_{eff} = /f_r = 6.4$. This value is close to $\epsilon_{eff} = 0.5(\epsilon_{Al_2O_3} + \epsilon_{PMMA}) = 6.1$, estimated from the resonator layout. A 5% difference can be explained by the influence of MgO substrate.



(a) (b)

Figure 3: Differential resistance vs. voltage dependence of JJ on MgO (a) and $NdGaO_3$ (b) substrates with open ring resonators of various sizes: 1 — 370 µm, 2 — 233 µm, 3 — 186 μm, 4 — 148 µm, 5 — 115 µm, 6 — 92 µm, 7 — 58 µm, 8 — 46 µm, 9 — 33 µm.

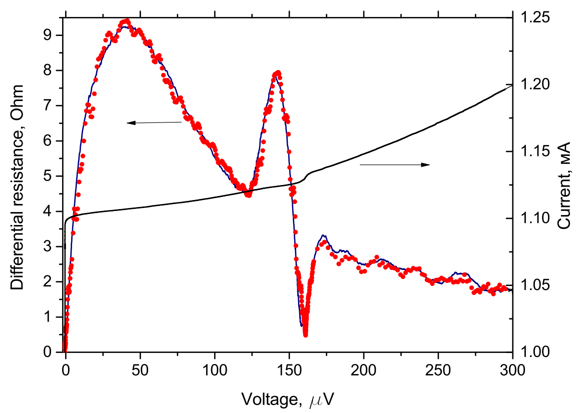


Figure 4: IV-curve and differential resistance vs voltage dependence of Josephson junction with 233 µm open ring resonators. Dotted line — measurement data, solid line — the results of numerical simulation.

5. CONCLUSION

Josephson spectroscopy was applied for frequency analysis of open ring resonators at. frequencies from 50 to 700 GHz. Planar resonators on separate wafers were attached to HTSC bicrystal Josephson junction and junction dc characteristics (IV-curve and $R_d(V)$) were measured. JJ characteristics shown features at voltage values, which correspond to resonance frequencies according to Josephson relation. A detailed analysis of 233 µm side length resonator was performed using numerical simulation of JJ with resonator based on RSJ model. A resonance frequency $f_r = 74.9$ GHz was obtain and resonator quality factor was estimated. It was shown that resonance corresponds to excitation of resonator LC-mode.

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