Linewidth Measurements of a Large Niobium Josephson Junction Array

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***Abstract*—We performed the spectral measurements of a niobium based Josephson junction array in order to estimate the linewidth of Josephson emission. The array is formed by 9996 serially connected Nb/NbSi/Nb Josephson junctions occupying the area of 5 × 7 mm^2 on a silicon substrate and divided into 7 distinct subarrays. The array was immersed in a liquid helium dewar from where the emission was brought to open space via an oversize waveguide. Firstly, the measurements on a Fourier-transform spectrometer were carried out in a wide frequency range 139–343 GHz at almost all self-induced steps of current-voltage curve. As in our previous work, the observed linewidth of Josephson emission corresponded to the resolution of the spectrometer. Then, we carried out more precise and sensitive measurements using the 211–275 GHz heterodyne receiver based on a Nb/AlO$_x$/Nb mixer with a spectral resolution better than 0.1 MHz. Dependencies of the linewidth on the step number and on the number of connected subarrays are studied. The peaks corresponding to the 2nd harmonic of the Josephson generation are also observed in the spectra. The linewidth of the main harmonic down to 1.5 MHz was observed in these measurements.**

***Index Terms*—Josephson junctions, spectrometry, superconducting devices, synchronization.**

I. Introduction

THE Josephson effect has a potential to solve many different fundamental and practical issues being at the forefront of physics: from high-sensitive detection of magnetic fields [1] and voltage standard [2] to quantum computing [3] and study of Majorana bound states [4]. All intricate properties of Josephson junctions (JJs) stem from coherent flow of Cooper pair currents through the barrier between superconducting electrodes. The first practical effect given by that flow is the ac Josephson effect binding the dc voltage V at the electrodes and the fundamental frequency of radiation f_J from the junction via only the fundamental constants. Typical characteristic voltage of JJ V_c brings f_J to the range from hundreds of GHz to tens of THz but with the emission power hardly exceeding picowatt level [5]. To increase the emission power to the values required for practical applications one have to organize arrays with thousands of junctions. This could bring some impact in solving the THz gap problem [6].

Interest to the THz generation by JJ arrays was revived due to considerable advances in the investigation of intrinsic JJs based on cuprate high-temperature superconductors (CHTSs), primarily on $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) [7]. However CHTSs have low heat conductance that leads to substantial self-heating [8], [9]. Single BSCCO mesa is not scalable in a sense of applications as a THz generator. Synchronization of several parallel connected mesas is a nontrivial issue with an unpredictable shift of the emission frequency [10]. Additional problem for CHTS based JJ array is a degradation in humid atmosphere that can limit the application [7], [11].

Due to huge amount of successive works with CHTS based intrinsic JJs the traditional discrete JJ arrays were somewhat forgotten in the problem of THz generation. However they always demonstrate high potential due to robust thin-film technology, variability in topology and practically unlimited scalability [5]. In last years the significant progress has been achieved in fabrication technology of Nb/NbSi/Nb junction arrays developed within the issues of voltage metrology [12], [13], [14]. Similar Nb/NbSi/Nb junction arrays with a special topology based on single-strip lines (SSLs) demonstrate a long-range synchronization of JJs provided by the excitation of cavity modes in the SSLs itself [15], [16], [17]. The off-chip radiation power detected in the vicinity of such array with 9000 JJs is estimated by more than 60 μW [18]. The emission power would be increased via the raise of the quality factor of the SSL resonators. Alternative way in the development of such JJ antennas is the excitation of traveling modes in the array [19], [20], [21]. In this case all junctions would be in equal electrodynamic conditions that removes restrictions in allowable number of synchronized JJs. Valuable obstacle in all Nb technologies is a small superconducting gap (SG) of Nb which limits the maximum emission frequency by several hundreds of GHz. This problem has to be overcome in future by replacing Nb with a higher SG material such as niobium nitride [22].

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Search of the best topology for JJ arrays would be facilitated by the measurements of the spectrum of Josephson emission. Measuring the linewidth of spectrum one can estimate the number of synchronized junctions [23] that is necessary in the study of synchronization mechanisms in JJ arrays of various topologies. Two types of techniques are commonly used in the spectrometry of JJs. First one is Fourier-transform (FT) spectrometry demanded in the study of synchronization of BSCCO mesas [9], [10], [24], [25], [26]. Having typical resolution $\sim$ 1–10 GHz, this technique usually allows estimating only the central frequency of the emission peak. For more sensitive measurements of spectrum the technique based on heterodyne mixing should be used. Today the most suitable device for this purpose is likely to be a superconducting heterodyne receiver based on niobium superconductor-insulator-superconductor (SIS) mixer. Combining an extremely high resolution, quantum sensitivity with a wide band tuneability in the range $\sim$0.1–1 THz [27] such SIS receiver has been used in linewidth measurements of BSCCO mesas [7], [28]. Recently it has been utilized for the spectrometry of a long JJ [29], [30]. SIS receivers were also used for spectral measurements of Nb JJ arrays but its operating frequencies did not exceed 80 GHz [31], [32].

In this work we have done comprehensive spectral measurements of large Nb/NbSi/Nb JJ array with almost ten thousand junctions and having overwavelength size. Firstly, the measurements on a FT spectrometer were carried out. As a result, we were able to follow a spectral line near averaged Josephson frequency f_J (i. e. averaged over all JJs in the array) moving along the current-voltage curve (IVC) in a wide range up to 343 GHz. The secondary peak near $2f_J$ (second harmonic) is also observed in some points of the IVC. Then, we carried out more precise and sensitive measurements using a SIS receiver. The linewidth down to 1.5 MHz has been achieved, provided the external noises have been minimized. The linewidth has been studied as the dependence on the points in the IVC and on the number of JJs in the array connected to the power circuit. Second harmonic of Josephson emission was also observed in the measurements with the SIS receiver.

II. Layout of the Array and Setup for the Off-Chip Emission

The JJ array chosen for the measurements is similar in its topology to one of the samples studied earlier in [18], [20], [33] (“6972 JJ array” or “linear array”). Compared to them, the present array has elongated SSLs with the length $L = 7.1$ mm, instead of $L = 5$ mm, and doubled distance between centers of adjacent SSLs in the same subarray, from 18 to 36 μm, Fig. 1(a). The array contains $N = 9996$ JJs. The dimension of junction, 8 $\times$ 8 μm, also as the characteristics of the silicon substrate, remains unchanged. Material of JJs is a compound Nb_xSi_{1-x} where $x \approx 0.1$. The sample is fabricated with the use of e-beam lithography and reactive ion etching [13], [34].

The JJ array was immersed to a liquid helium dewar where it was cooled to a temperature of $T = 4.2$ K. Special setup based on a 1 m long stainless-steel tube was used to bring the Josephson emission outside the dewar. This tube contains inside

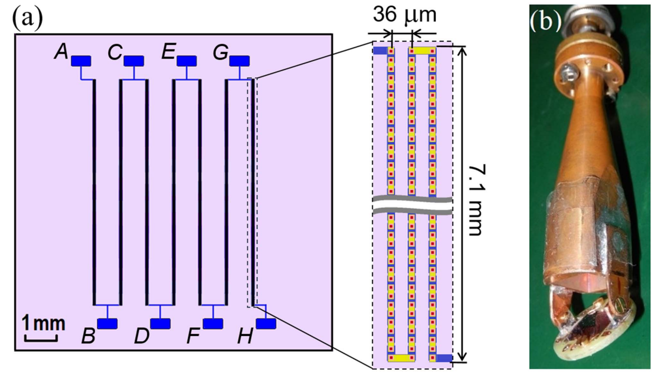

Fig. 1. (a) Topology of the JJ array. It consists from 7 distinct subarrays with 3 SSLs in each. One subarray with values of space parameters is shown in the inset. Each SSL contains 476 Nb/NbSi/Nb junctions (red squares in the inset) formed in the overlap of top (yellow rectangles) and bottom (blue partly covered rectangles) electrodes. The array is on a 1 $\times$ 1 cm Si substrate. Letters from A to H indicate contact pads between adjacent subarrays. (b) Chip with JJ array fixed on a holder is ahead a 12 $\times$ 12 mm aperture of the horn which collects Josephson emission and brings it outside the dewar.

a microwave waveguide system composed of a 12 $\times$ 12 mm square horn, a WR12 tapering and a 11 $\times$ 5.5 mm rectangular waveguide. The chip with the JJ array was placed opposite to the horn aperture in the lower end of the tube which was immersed in the dewar, Fig. 1(b). Emission generated by the array is collected by the horn, passes through the taper, which cuts off the higher order modes, and then travels along the rectangular waveguide. At the higher end of waveguide the emission goes out to the room. Dimension of the waveguide is oversize relative to the range of wavelength. This allows reducing the electromagnetic dissipation on the walls of waveguide in comparison with a single-mode waveguide. While the horn and the taper are copper the oversize waveguide are made from stainless-steel to reduce the heat transition from the room to the array. The chip was surrounded by a cryoperm shield to prevent the array from parasitic magnetic field.

Note that the chip was oriented at the angle $\sim$45° to the aperture in the plane perpendicular to the SSLs, Fig. 1(b). As was experimentally found, at such angle the off-chip Josephson emission power from this array is maximal and reaches 3 μW in the frequency range 140–200 GHz at the exit of the dewar. This confirms the fact that resonant modes excited in such overwavelength Nb arrays contain travelling wave components, as it was predicted theoretically [19], [21] and identified in the previous measurements [18], [20]. Due to travelling wave components, the angular distribution of Josephson emission relative to the surface of sample must be asymmetrical.

III. Fourier-Transform Spectrometry

FT spectrometry of the JJ array was performed on a high-resolution spectrometer Bruker IFS 125HR while the emission was detected at the exit of the spectrometer by a Si-bolometer from Infrared Laboratories with a noise equivalent power of 2×10^{-13} W/Hz$^{1/2}$. All this equipment was used earlier in [33] for spectral measurements of similar Nb JJ arrays. The oversize waveguide bringing the Josephson emission outside

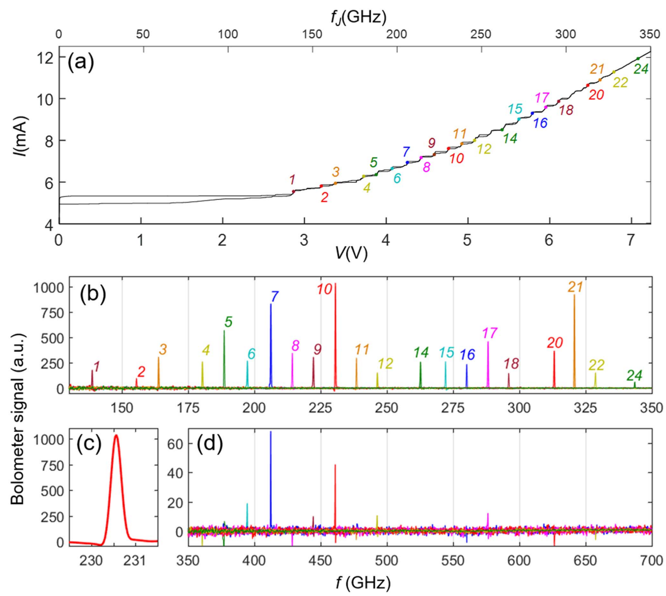

Fig. 2. (a) IVC of the JJ array, all subarrays are connected. FT spectrometry was carried out in indicated points. The numbers nominally mark the current steps. Upper axis denotes an averaged Josephson frequency defined from $V_1 = V/N$ via the Josephson relation. (b) Parts of the spectra obtained by FT spectrometry with peaks of the first harmonics of Josephson emission. The numbers near the peaks are related with the numbers indicated in the IVC. (c) Enlarged view of the peak obtained at 10th step. The width of this peak also as all others is near 300 MHz, that corresponds to the resolution of the spectrometer. (d) Parts of the spectra where peaks of the second harmonics of Josephson emission are possibly registered. The graphics is aligned with the spectra in (b) so the peaks of the second harmonic are directly under the peaks of the first one.

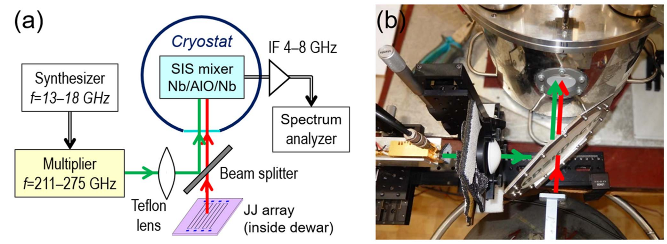

Fig. 3. Block diagram (a) and photo (b) of the SIS receiver used for the spectral measurements of emission from the JJ array. The arrows show paths of the beams which output from the multiplier (green) and from the end flange of the oversize waveguide delivered the emission of the JJ array from the dewar (red).

the dewar has been extended directly to the input splitter of the spectrometer. A miniature 13 mm diameter Teflon lens was glued to the end flange of this waveguide. This lens helped to collect the emission onto the spectrometer aperture.

Fig. 2(a) demonstrates IVC of whole JJ array when a current supply and a voltmeter both connect to contact pads A and H, see Fig. 1(a). Comparative to previous arrays measured in [33], this array has higher critical current $I_c = 5.5$ mA and increased characteristic voltage $V_c \approx 280$ mV that provides characteristic frequency $f_c \approx 140$ GHz. The IVC contain more than 20 distinct current steps located through $\Delta f_J = 8.2$ GHz in average. These are self-induced steps which are caused by the resonant modes excited along the SSLs of the array. This is additionally proved by the fact that, in comparison with "6972 JJ" array [18], [20], [33], the value of Δf_J decreased strictly proportionally to the elongation of SSLs, i. e. the product $L\Delta f_J = 58.2$ mm·GHz for present array is very close to the product $L\Delta f_J = 5$ mm·11.8 GHz $= 59$ mm·GHz for "6972 JJ" array [18]. Doing the calculation as in [18] we obtain that the 1st step in Fig. 2(a) corresponds to 17th resonant mode.

A recording of any spectrum of Josephson emission was carried out when the operating point of the IVC was biased to a certain current step. The FT spectral measurements were performed at almost all current steps. In each spectrum the peak of the first Josephson harmonic was always observed at the frequency $f \approx f_J$, Fig. 2(b). The rightmost peak has been written at bias current $I = 11.9$ mA, on a hardly visible 24th step. This peak is located at $f = 343$ GHz that is much larger than f_c. Amplitudes of the peaks vary in a wide range and are defined rather by the radiation pattern of the JJ array which can be significantly different at close operating points [21]. All the peaks have the width $\Delta f \approx 300$ MHz that coincides with chosen resolution of the spectrometer, Fig. 2(c). As in the previous spectral measurements [33], this means that the linewidth of emission from JJ array has to be less than the resolution of the spectrometer. Therefore we further should use more sensitive device for the spectrometry of Nb JJ array.

Some spectra also demonstrate additional peak at $f \approx 2f_J$, up to $f = 658$ GHz (22nd step), Fig. 2(d), with the same width. It can be assumed that second harmonics are observed in those cases. However, reliability of those peaks is needed in additional verification because the presence of 2nd harmonics in FT spectrometry can be a result of parasitic reflections inside the interferometer branches [35]. Suspicion about this effect is supported by the fact that some peaks in Fig. 2(d) have negative amplitudes.

IV. Spectral Measurements by a SIS Receiver

More precise and sensitive measurements were carried out on a SIS receiver [36]. It includes a solid-state multiplier radiating at $f = 211$–275 GHz and a Nb/AlO$_x$/Nb SIS mixer, Fig. 3. The mixer is cooled down to $T = 4.2$ K in a close-cycle cryostat. The radiations from the multiplier and from the JJ array unite at a beam splitter and then come to the mixer through an optical window of the cryostat. Amplified down-converted signal is finally displayed on a spectrum analyzer, Fig. 3(a). The receiver has extremely low noises on the quantum level (noise temperature ~70 K) and the resolution better than 0.1 MHz.

In the measurements we analyzed the spectral lines of the Josephson emission in the intermediate frequency (IF) range 4–8 GHz. As in the FT spectrometry, at any current step of the IVC we obtained a peak of the fundamental harmonic. However, the spectrum strongly depended on the operating frequency as well as on outside interference and crosstalk appearing in the setup in varying extent. The highest IF signal of the receiver was observed at 12th step located in the range $f_J \approx 244$–246 GHz, Fig. 2(a). The width of the peak of the fundamental harmonic was mostly in the range 3–6 MHz. We then carried out work on elimination the technical noises as much as possible. This is resulted in decreasing of the linewidth down to 1.5 MHz,

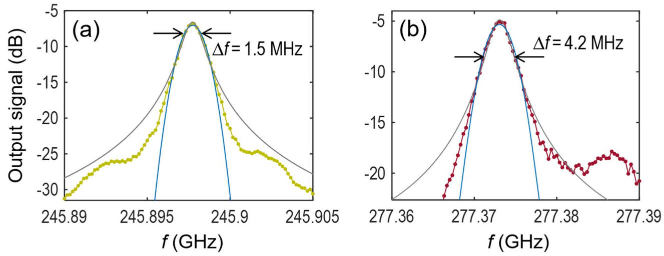

Fig. 4. (a) Peak of the first harmonic of Josephson emission measured at the 12th current step of the IVC of the JJ array. (b) Peak of the second harmonic measured at the 1st step. Both peaks are approximated by Lorentzian (gray line) and Gaussian (blue line) functions using the least square method.

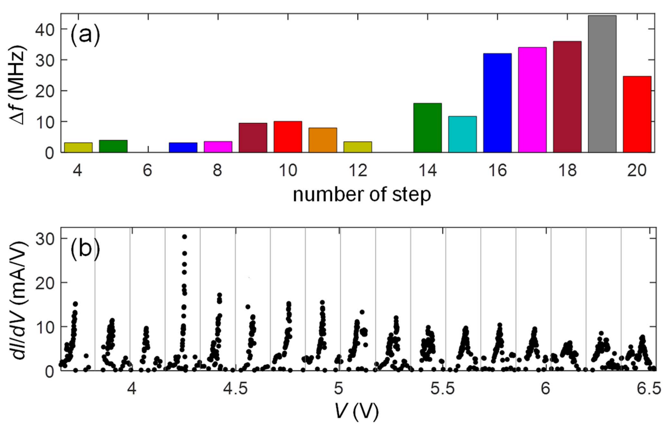

Fig. 5. (a) Dependence of the linewidth of the first harmonic measured by the SIS receiver on a current step number. (b) Differential conductance of the JJ array calculated along the resistive branch of the IVC, Fig. 2(a). Vertical lines demarcate the positions of current steps through every $\Delta f_J = 8.2$ GHz.

Fig. 4(a). As shown in Fig. 4(a), the peak is not perfectly well approximated by the Lorentzian function. This indicates that the technical noises still have presented in the setup and have noticeably expanded the spectrum [37].

We also succeeded in registration of the second harmonic of Josephson generation. The measurement was performed on the 1st current step located at $f_J = 139$ GHz. The peak was observed at nearly doubled frequency $f \approx 2f_J$ with the width $\Delta f = 4.2$ MHz, Fig. 4(b). The Lorentzian approximation is also far from ideal in this case, that indicates an impact of the technical noises.

Measurements of the first harmonic of Josephson generation were performed in a wide frequency range, on most of the current steps of the IVC. Fig. 5(a) shows the measured linewidth on different steps from 4th to 20th. As seen, $\Delta f = 3$–4 MHz in lower half of step series, locally increasing to 8–10 MHz on the steps from 9th to 11th. Note that here $\Delta f = 3.5$ MHz at the 12th step, in contrast to the results in Fig. 4(a), because Fig. 5 relates to other measurements with higher external noises. After the 12th step Δf is starting to rise and achieves maximum 44 MHz at 19th step. Generally, we can conclude that Δf tends to grow with the increase of step number. At the same time, the differential conductance G_d calculated along the resistive branch of the IVC slowly decreases in most part of step series beginning at the 8th step, Fig. 5(b). This is in accordance with the prediction from the resistively shunted junction (RSJ) model where the linewidth Δf must increase together with the increasing of differential resistance $R_d = 1/G_d$ [37]. Note that low-frequency external noises only decrease the power n in the relationship $\Delta f \sim R_d^n$, i. e. $\Delta f \sim R_d^2$ for the Lorentzian line and $\Delta f \sim R_d^{1/2}$ for the Gaussian line [37].

We also studied the linewidth of the first harmonic at the connection of different parts of the JJ array, from 1 to 7 subarrays, see Fig. 1(a). These measurements were performed at the 12th step. We saw that the linewidth doesn't practically change when from 3 to 7 subarrays are connected, staying at $\Delta f \approx 1.5$ MHz. But at 2 active subarrays (AB&BC) the linewidth increases to $\Delta f = 11$ MHz while for 1 active subarray (CD) we have $\Delta f = 4$ MHz. We can give two explanations of observed nontrivial dependence. The first one is that the electromagnetic interaction of 2 adjacent subarrays leads to desynchronization of JJs in each of them therefore Δf grows. The addition of third subarray changes the situation. Significant part of junctions is now becoming synchronized leading to the narrowing of the spectral line. Connection of more subarrays doesn't longer influence to the synchronization so Δf remains stable. The second explanation concerns only the anomalous linewidth at 2 active subarrays. Corresponding part of the array AB&BC may just characterized by much larger parameter scattering of JJs in comparison with the subarray CD. This can determine such nonmonotonic evolution of Δf.

V. Conclusion

We performed spectral measurements of large Nb/NbSi/Nb JJ array with the use of a FT spectrometer and a SIS receiver. The FT spectrometry allowed to register a spectral line of the first harmonic of Josephson emission in a wide frequency range $f = 139$–343 GHz, at more than 20 self-induced current steps on the resistive branch of the IVC. At some steps additional peaks were also observed at near doubled Josephson frequency, which can be attributed to the second harmonic of Josephson radiation. The FT spectrometer proved to be a crude tool for the measurements of linewidth of the Josephson emission because the width of all measured peaks coincides with the resolution of the spectrometer ~300 MHz.

The linewidth measurements have been accomplished by the SIS receiver. Minimizing external interference and technical noises we measured the linewidth $\Delta f = 1.5$ MHz for the peak of the first harmonic at $f = 245.90$ GHz. The peak of the second harmonic was also observed at $f = 277.37$ GHz with the width $\Delta f = 4.2$ MHz. All the peaks are far from a Lorentzian approximation indicating that technical noises still expand the spectrum. The linewidth of the first harmonic generally increases with the growth of step number. This is in accordance with the RSJ model which predicts a direct dependence between Δf and differential resistance R_d on the current step. We also studied how the linewidth depends on the radiation of different parts of the JJ array which is divided on 7 distinct subarrays. We revealed that connecting three subarrays significantly narrows the linewidth of the first harmonic while connecting more subarrays doesn't influence the spectrum.

We are planning to further perform spectral measurements of Nb JJ arrays on the SIS receiver. The issues at the forefront are the study of synchronization of junctions inside the array based on the data of the linewidth measurements and the realization of a phase locking loop system for narrowing the Josephson spectrum. The latter will allow considering a large JJ array as a heterodyne in integrated SIS receivers.

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