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Experimental study of a harmonic mixer based on a series chain of YBaCuO bicrystal Josephson junctions in zero-bias operation

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Sequential chains of HTS Josephson junctions with an optimized log-periodic antenna operating in the THz signal mixing regime have been calculated, manufactured and measured. It is shown that the synchronous operation of the junctions leads to an increase in the integral absorbed power and, as a result, an increase in the dynamic range. Two regimes were found: at low temperatures, coordinated excitation of junctions in the chain is observed, at high temperatures, „giant" Shapiro steps appear, indicating synchronization of junctions. The characteristics of the mixer have been studied using the mixing operation with the higher harmonics of the heterodyne signal. For an optimal pumping level with a frequency of 3 GHz, a non-zero amplitude of the intermediate frequency was detected when mixed with a 120 GHz signal at 40 harmonics. It is shown that in the optimal regime of operation of the mixer, the configuration of the series chain allows the use of the zero offset regime.

Keywords: high-temperature superconductor, Josephson junction, harmonic mixer, series chain.

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1. Introduction

Superconducting devices based on Josephson effects feature unique harmonic generation and mixing properties that have been used in experiments since the late 1960s. It is known that various operation regimes of the harmonic mixer [1–3] are possible in Josephson junctions. However, mixing based on Josephson nonlinearity was previously considered as a parasitic effect resulting in an additional noise, therefore, the critical current is suppressed in superconductor-insulator-superconductor mixers. But recent studies have shown the possibility of conversion in the Josephson regime without a significant increase of the noise [4–6].

Although high-temperature superconductors (HTSC) have long been considered as promising materials for the creation of high-frequency Josephson devices, recent impressive results in this field [7,8] give a new impetus to this field of studies.

Rather low impedance of Josephson junctions (JJ) is one of the main disadvantages of HTSC technology. The normal resistance of the R_N junction usually equals to several Ohms for the standard geometry of junctions with a width of $2-3\,\mu$m, which does not correspond to the characteristic impedance of antennas or coplanar lines of the order of 50 Ohms.

The replacement of one junction with a series chain of junctions is a possible solution to this problem. The received signal power and impedance can be increased to the level of practical application if all junctions in the serial array operate in synchronization regime. In addition, the JJ array can also solve the problem of saturation of a harmonic mixer that takes place with the increase of the signal frequency or harmonic order. The signal-to-noise ratio was increased at the output of the intermediate frequency (IF) by 5 dB in Ref. [9] by mixing the 11th harmonics. It was observed in Ref. [10] that the amplitude of IF very weakly depends on the offset point of the HTSC junction chain. Therefore, a mixer with a Josephson junction can operate with a zero offset and this has the great advantage because a DC source is not required and therefore there is no heating effect or shot noise in the junction attributable to the DC.

A Josephson zero-offset mixer consisting of three consecutive YBaCuO bicrystal junctions connected by a meander and integrated into a log-periodic antenna is demonstrated in this paper. Shapiro steps were studied at different sample temperatures for different GHz signal frequencies. Two regimes were found: a mismatched excitation of junctions in the chain is observed at low temperatures, giant Shapiro steps appear at high temperatures which indicate synchronization of junctions. Mixing of signals at high harmonics is demonstrated.

2. Electromagnetic regimeling

Electromagnetic regimeling of a mixer with a log-periodic antenna was performed at the first stage (Figure 1, *a*) to

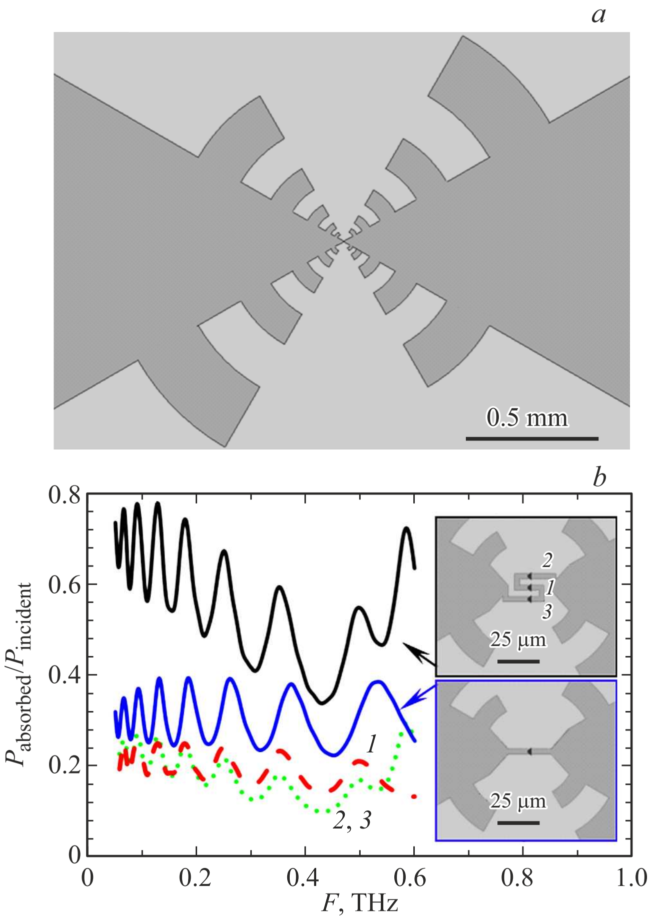

Figure 1. *a* — log-periodic antenna, *b* — the ratio of absorbed power to incident power for two different cases. Blue curve — one junction in the antenna; black curve — three consecutive junctions. Red dotted line — absorption at the central junction of the chain. Green dots — absorption in the extreme junctions of the chain. On the inserts — the geometry of the central part of the mixer for two cases.

obtain effective signal reception in the frequency range of 50−600 GHz [11]. CST Microwave Studio program was used to perform simulation. The finite difference method was used as a numerical method. The substrate parameters were selected in accordance with experimental data: substrate thickness — 0.5 mm; dielectric constant — 24, loss tangent — 0.0045. The amplitude-frequency response (AFR) of the system and the radiation pattern are studied. A smooth amplitude-frequency response was obtained over the entire frequency range for the case of usage of a single Josephson junction as a receiving element with a maximum response of $0.39P_{incident}$ and the magnitude of the main lobe of the radiation pattern of 15.7 dBi at an angular width of 15°. A design with three consecutive Josephson junctions was considered to improve the alignment between the receiving system and the antenna. Figure 1, *b* shows that the integral power absorbed by three junctions is 2.3 times greater than the power absorbed by one junction. In addition, it can be seen that the positions of the resonances of the amplitude-frequency response for the case of a series chain differ from the resonances for a single strip. And the higher the frequency, the stronger the differences. Moreover, the AFR for the „extreme“ ports begins to differ markedly from the frequency response of the central port from 500 GHz. Additional resonances appear above 500 GHz. This is attributable to the inductance of the meander, whose impedance is estimated to be approximately 30 Ohms per 500 GHz. Therefore, the reduction of the length of the meander becomes important in case of operation at high frequencies. The kinetic inductance of the HTSC superconductor, which is key for certain tasks, was not taken into account in this model. In this case, we estimated the kinetic inductance using the formula [12] L^k (per square) $= \mu_0/2\lambda_L = 10^{-13}$ H, where μ_0 — magnetic constant, $\lambda_L = 0.15\,\mu$m — London penetration depth in YBaCuO superconductor. Thus, the kinetic inductance was $2 \cdot 10^{-12}$ H, and the impedance at 500 GHz−6 Ohm. The value is close to the impedance of the geometric inductance, and should be taken into account in the model in the future.

Although the integrated received power of the chain increases because of better matching with the antenna, each individual junction in the array receives less power than in the case of a single JJ in the antenna. The elements distribute power among themselves due to the serial connection to a common receiving system. The greater is the number of elements, the less power is supplied to each individual junction. This also allows increasing the dynamic range of the receiver.

3. Measurement scheme

The signal was mixed on the basis of the Josephson effect in the HTSC superconductor. The YBaCuO film of a superconductor with a thickness of $0.1\,\mu$m was sputtered by the setting mask method [13] onto the surface of a bicrystal $Zr_{1-x}Y_xO_2$ substrate with a misorientation angle of 24° in the plane [001]. The bridge crossed the bicrystal boundary 3 times, so that the result was a chain of Josephson junctions, each of which had a width of $3\,\mu$m. The chain was integrated into a log-periodic planar antenna for broadband communication with external radiation (Figure 2).

The HTSC mixer was installed on a silicon lens in the Gifford-McMahon cryohooler, Figure 3. The useful signal from the reverse wave lamp was transmitted using a quasi-optical scheme with a fluoroplastic lens, infrared filters and a supersized waveguide.

The signal at the intermediate frequency was obtained using the operation of mixing with the higher harmonics of a heterodyne signal, which was emitted using a monopole antenna and received by a mixer. The length of the monopole antenna was 4 mm, and the distance to the sample was 2 mm. Microwave generator R&S SMB100A with a frequency range from 100 kHz to 20 GHz was used as a source of the heterodyne signal. The same antenna was used to transmit the heterodyne signal. For

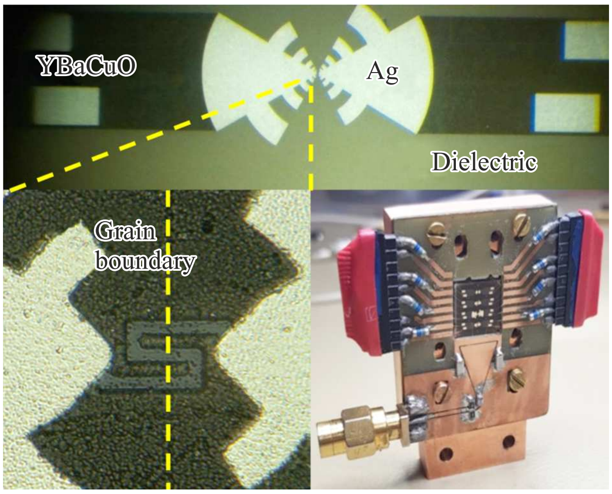

Figure 2. Photo of the HTSC harmonic mixer. Top — YBaCuO film with antenna and contact pads made of silver. Bottom left — the area near the bicrystal boundary. Bottom right — a sample mounted on a holder.

this reason the amplitude-frequency response was severely cut, and the losses were 20–30 dB. We could choose the optimal power of the heterodyne for each frequency because high power is not required to pump the HTSC mixer. However, this method of transmitting the reference signal is suboptimal, therefore, another scheme is currently implemented in which the heterodyne signal is transmitted via a coaxial cable to the mixer board using a diplexer. The intermediate frequency signal was recorded using Gratten GA spectrum analyzer. Preamplifier SBB5089Z, located on a cold cryostat plate, together with a room amplifier provided a gain of 52 dB at noise −64 dBm in the frequency range 1–3 GHz in the band of 3 MHz. The noise of the spectrum analyzer itself was approximately −90 dBm in 3 MHz band and provided a small addition to the noise of the system. A battery-powered DC power source was used to control the mixer.

4. Results

Figure 4, *a* shows the measured current-voltage characteristic curve (I-V curve) of the mixer as a function of temperature. Sharp changes of the slopes of the I-V curve are visible For low temperatures of 50–10 K, due to the junction from the superconducting state to the resistive state of each of the junctions separately. Figure 4, *b* shows the critical current I_C depending on the temperature. The spread of the critical current among the junctions was $\sim 20\%$. At the same time, as expected, $R_N\,(3\,\mathrm{JJ}) \sim 3 \times R_N\,(1\,\mathrm{JJ})$. Despite the significant variation of the junction parameters, the array demonstrates a I-V curve close to the resistive model predictions at high temperatures, and it can be expected that the junctions will be synchronized by external radiation.

Figure 5 shows the I-V curve of the mixer exposed to external high-frequency radiation of $f_{\mathrm{THZ}} = 130\,\mathrm{GHz}$ of different power at two temperatures. The voltage was normalized by one junction to study the synchronous states of successive junctions, that is, the measured value V was divided by 3. Many Shapiro steps appear on the I-V curve at a low temperature of 10 K. Black dotted lines indicate voltages satisfying the Josephson dependence of voltage on frequency, gray dotted lines show voltages at 2/3 step voltages, light gray dotted lines show voltages at 1/3 voltages. All Shapiro steps corresponding to states with synchronization [14] are at voltages satisfying the Josephson ratio of $V/3 = n\Phi_0 f_{\mathrm{THZ}}$, where n — the number of the whole Shapiro step, Φ_0 — the quantum of the flow. The synchronization state here refers to the synchronization that takes place as a result of resonance with a high-frequency

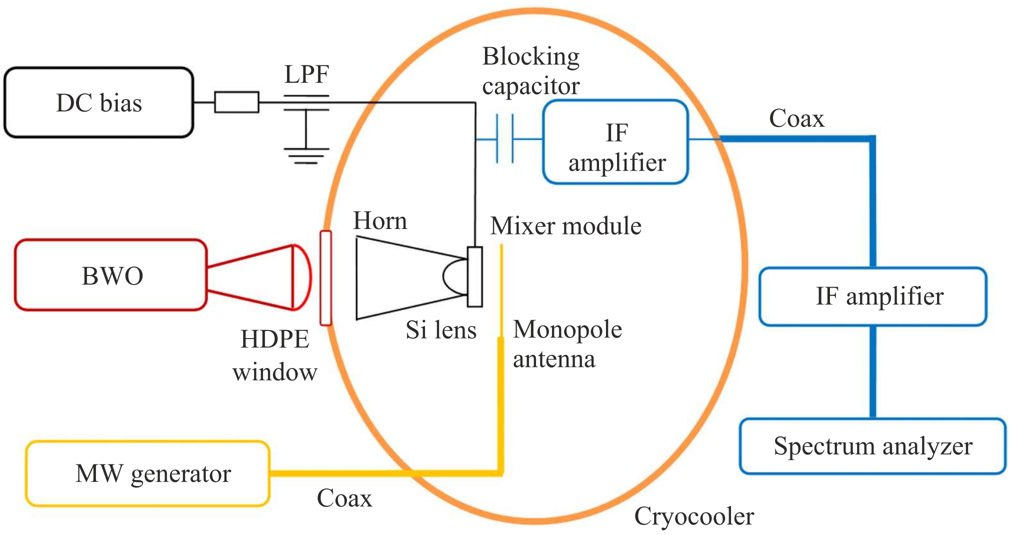

Figure 3. The scheme of spectral measurements.

effect. The step at voltage $\Phi_0 f_{\mathrm{THZ}}/3$ indicates that only one junction is synchronized, the step at voltage $2\Phi_0 f_{\mathrm{THZ}}/3$ — two junctions, and so on.

At a temperature of 77 K, the „giant“ Shapiro steps are visible on the volt-ampere characteristic only at voltages $n\Phi_0 f_{\mathrm{THZ}}$, which indicates the synchronous operation of all three junctions.

Harmonic mixing experiments were carried out at a temperature of 77 K. Figure 6 shows the current-voltage curve under the action of a low-power high-frequency signal of 175 GHz and a pump signal with a frequency of ~ 21.6 GHz. The magnitude of the line at the intermediate frequency P_{IF} (left axis in Figure 6) usually has a maximum in the center of the Shapiro step. This behavior was observed in case of a single junction [16,17]. But, unlike a mixer with a single junction, the array demonstrates a maximum of IF near zero current, comparable to the absolute maximum of the amplitude of the intermediate frequency for these conditions.

Further studies allowed finding the amplitude of the intermediate frequency line in case of mixing of the 120 GHz signal and the 40 th harmonics of the reference signal with a frequency of 3 GHz. Moreover, the dependence of the amplitude IF on the pumping power was studied when mixing the signal 170.22 GHz and 17 th harmonics of the reference signal of 9.973 GHz; as well as 33 th harmonics of the reference signal of 5.137 GHz.

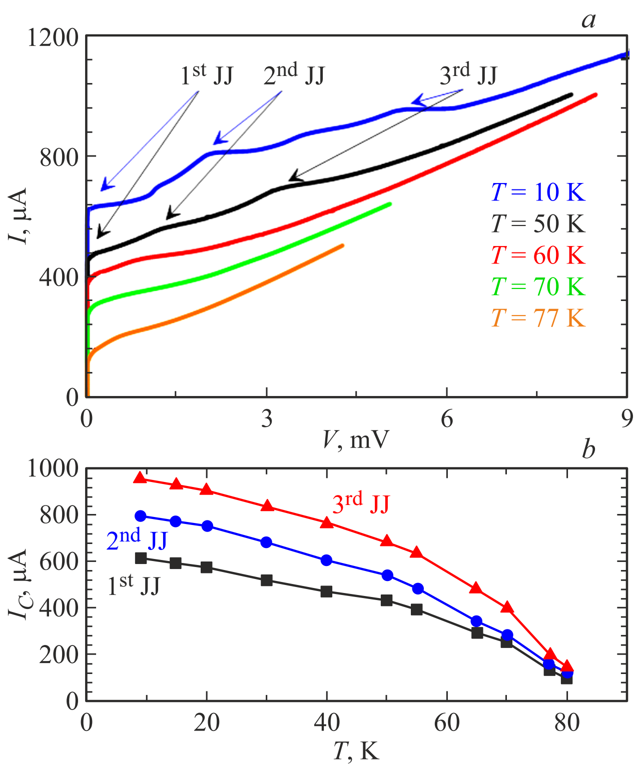

Figure 4. *a* — I-V curves of the mixer at various temperatures. The arrows show the exit from the superconducting state of each junction in the chain. *b* — the dependence of the critical current on the temperature for each junction in the chain.

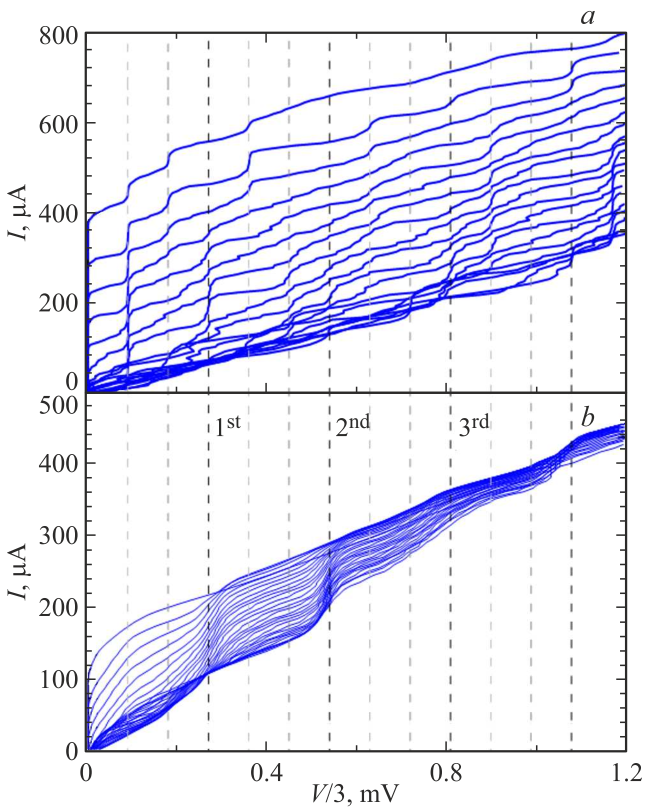

Figure 5. The current-voltage curve of the mixer under the impact of an external signal of 130 GHz. Black dotted lines — the position of the first Shapiro step is normalized by one junction. *a* — mixer temperature $T = 10$ K. *b* — mixer temperature $T = 77$ K.

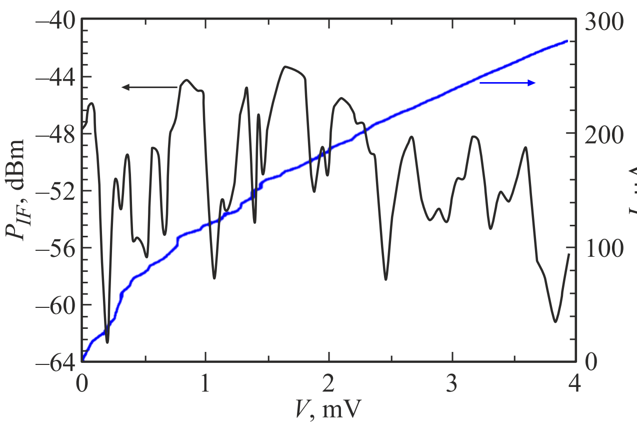

Figure 6. The current-voltage curve of the mixer under the impact of an external signal 175 GHz and a reference signal 21.6 GHz. Left axis — amplitude of the intermediate frequency line, right axis — direct current on the mixer.

5. Conclusion

Sequential chains of HTSC Josephson junctions with an optimized log-periodic antenna were calculated, manufactured and measured as a result of the study. It was demonstrated that the synchronous work of the junctions results in an increase of the integral absorbed power and, as a result, an increase of the dynamic range. The characteristics of the mixer were studied using the operation of mixing with the higher harmonics of the heterodyne signal. As a result, a non-zero IF amplitude was found when mixing the 120 GHz signal and 40 th harmonics of the reference signal with a frequency of 3 GHz. It was demonstrated that the configuration of the series chain in the optimal regime of operation of the mixer allows using the zero offset regime, as well as achieving mixing at a high harmonic of the reference signal.

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Conflict of interest

The authors declare that they have no conflict of interest.

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