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Investigation of the current-voltage characteristics of arrays of Josephson junctions from high-temperature superconductors under pulsed irradiation

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The current-voltage characteristic and voltage spectrum of a Josephson junction under the action of current pulses are studied within the framework of a resistive shunt model. The possibility of using Josephson junctions made of high-temperature superconductors to create a quantum synthesizer of alternating voltage has been studied.

Keywords: high-temperature superconductors, Josephson junctions, microwave, quantum synthesizer.

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1. Introduction

The most accurate and reproducible DC voltage standards are based on the superconducting Josephson junctions [1,2]. Modern technology of manufacturing Josephson junctions from niobium allows to synchronize chains containing several tens of thousands of contacts by an external signal [2]. In 1996, to implement the AC voltage standard, Benz and Hamilton offered a random waveform synthesizer based on niobium Josephson junctions [3,4]. In the synthesizer, a chain of Josephson junctions is controlled by current pulses, which allow to generate a variable random waveform with quantum accuracy [5–7]. Currently, quantum random waveform synthesizers based on low-temperature superconductors are used in the Johnson thermometry, AC voltage standards, thermal converter calibration, etc., [6]. However, the need to cool down niobium microchips to the liquid helium temperature results in high operational cost. At the same time, the arrays of bicrystalline Josephson junctions made from high-temperature superconductors (HTSC) are attractive for building a quantum random waveform synthesizer [8.9]. This is because the operating temperatures for these microchips can be achieved using low-power compact cryocoolers. However, voltage standards based on low-temperature superconductors use special types of Josephson $Nb/Nb_xSi_{1-x}/Nb$ contacts [10] that are poorly described by the standard resistive shunted contact model. therefore, the problem of synchronization of Josephson junction arrays based on high-temperature superconductors with pulsed irradiation is still open.

The study investigates current-voltage curves (IVC) and voltage spectrum for the Josephson junction exposed to current pulses within a resistive shunted model. Possibility of synchronization of these contacts by external pulsed irradiation is shown. It has been also found that the voltage spectrum contains only the fundamental harmonic of pulse signal modulation frequency.

2. Microchip

Earlier in [11], numerical simulation was carried out and design of an microchip was developed for the array of bicrystalline Josephson junctions from high-temperature superconductors embedded in a coplanar transmission line. It is shown that the structure produced *in situ* has a low value of contact resistance, which allows to obtain high-quality shunted Josephson junctions from high-temperature superconductors. For the *in situ* structure, synchronization of the chain of ten Josephson junctions with external microwave signal was obtained.

Figure 1 shows a photo pattern of such microchip. The contacts were made by deposition of high-temperature $YBa_2Cu_3O_7$ (YBCO) superconductor on a bicrystal substrate made from zirconium-stabilized yttrium oxide(YSZ). The bicrystal substrate consists of two crystals turned with respect to the bicrystal boundary at 12°. On these substrates 10×10 mm in size and 0.5 mm in thickness, an epitaxial film is first grown from high-temperature YBCO superconductor 100−300 nm in thickness and then coated with a thin gold layer. When the YBCO film is deposited, a damaged layer is formed at the bicrystal boundary resulting in the occurrence of a Josephson junction. These contacts are SNS type junction (superconductor−normal metal−superconductor). Shunting is required to reduce the scatter of normal contact resistances. standard photolithography and argon etching are used to manufacture the microchip. As a result, a chain of Josephson junctions

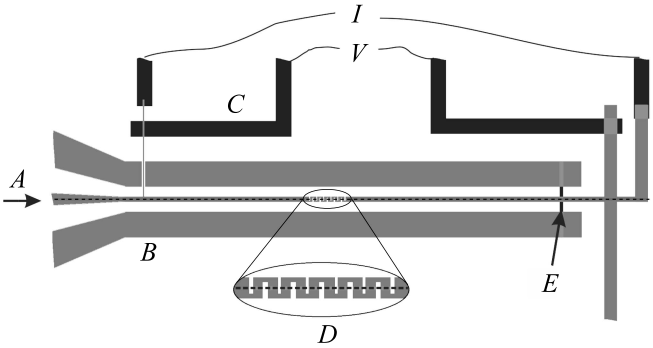

Figure 1. Photo pattern for the Josephson junction array made from high-temperature superconductors built in a coplanar transmission line. (*A* is the microwave power, *B* is the YBCO/Au coplanar transmission line, *C* are the NbN electrodes for passage of current and voltage measurement; *D* is the meander, *E* is the load). The dashed line shows the bicrystalline boundary.

in the form of meander $10\,\mu$m in width is formed. The Josephson junctions are formed at the intersection between bridges and bicrystal boundary.

Dimensions of the coplanar transmission line were chosen so that its wave resistance and load impedance were equal to $50\,\Omega$. To reduce penetration of microwave power into the measurement path, filters in the form of high-resistance electrodes made by 300 nm NbN film deposition are used.

3. IVC of the Josephson junction exposed to pulse irradiation

The study addresses synchronization of a chain of shunted bicrystal Josephson junctions made from high-temperature superconductors by pulsed irradiation. Since these contacts are of SNS type, a resistive shunted model may be used to simulate this effect [12]. Generally, a Josephson junction in a resistive shunted model is represented in a form an ideal Josephson junction, resistor and capacitor connected in series. The McCumber parameter $\beta_c = 2eI_cR_n^2C/\hbar$ for shunted bicrystal Josephson junctions made from high-temperature superconductors may be estimated, where I_c is the critical junction current, R_n is the shunt resistance and C is the junction capacity. However, its capacity $C = \varepsilon_0 S/d$ (S — contact area, d — damaged contact layer width) may be determined from its dimensions. By substituting $I_c = 0.4\,\text{mA}$, $R_n = 0.1\,\Omega$, $S = 3\cdot 10^{-12}\,\text{m}^2$, $d = 10\,\text{nm}$ [11] into the expression for the McCumber parameter, we obtain than in our case $\beta_c = 3\cdot 10^{-5}$. Thus, in case of shunted bicrystal Josephson junctions made from high-temperature superconductors, the capacity of contact in this model may be neglected.

Write the Josephson junction dynamic equation in dimensionless form in case pulse-frequency modulation of current $\omega(t) = \omega_0 + \omega_1\cos\Omega t$:

$$\dot\varphi + \sin\varphi = \bar i + \alpha\sum_{k=1}^{\infty}\cos(k\omega_0 t + kM\sin\Omega t), \tag{1}$$

where $M = \omega_1/\Omega \sim 1$ — is the modulation coefficient, a is the current pulse amplitude and $\Omega \ll 1$. In (1), the alternating current component is a periodic sequence of delta functions with a variable pulse repetition rate $\omega(t)$. Consider the „high-frequency limit“ case, i.e. when $\omega_0 a \gg 1$. For solution of equation (1), use the successive approximation method. Then, (1) may be rewritten as a system of two equations

$$\dot\varphi_0 = \bar i + a\sum_{k=1}^{\infty}\cos(k\omega_0 k + kM\sin\Omega t),$$

$$\dot\varphi_1 = -\sin(\varphi_0) + \bar i_1. \tag{2}$$

In the adiabatic approximation, i.e. when $\Omega\Box\omega_0$, the first equation may be integrated with respect to time:

$$\varphi_0 = \bar i t + \frac{a}{\omega_0}\sum_{k=1}^{\infty}\frac{\cos(k\omega_0 t + kM\sin\Omega t)}{k}. \tag{3}$$

Calculating the sum in the second term in (3), we finally find φ_0 [4]:

$$\varphi_0 = \bar i t - \frac{a}{2\omega_0}(\omega_0 t + M\sin\Omega t) + \chi - \frac{a\pi}{2\omega_0}, \tag{4}$$

where χ is a slowly varying phase. Then, be substituting φ_0 into the second equation of system (2), we obtain the reduced equation for χ:

$$\dot\chi + \sin\left(\bar i t - \frac{a}{2\omega_0}(\omega_0 t + M\sin\Omega t) + \chi - \frac{a\pi}{2\omega_0}\right) = \bar i_1. \tag{5}$$

This equation show that synchronization of the Josephson junction by external current pulses occurs at $\bar i = n\omega_0$ and $a = 2n\omega_0$. In this case, write the equation for the first Shapiro step ($n = 1$)

$$\dot\chi - \sin(\chi - M\sin\Omega t) = \bar i_1. \tag{6}$$

Replacing $\Theta = \chi - M\sin\Omega t$, equation (6) may be rewritten as:

$$\dot\Theta - \sin\Theta = \bar i_1 - M\Omega\cos\Omega t. \tag{7}$$

Since $M\Omega \ll 1$ and $\bar i_1 \ll 1$, equation (7) may be solved the successive approximation method:

$$\dot\Theta = -M\Omega^2\sin\Omega t + \frac{1}{2}\bar i_1 M^2\Omega^3\sin 2\Omega t - \frac{1}{4}M^3\Omega^4\sin 3\Omega t. \tag{8}$$

Note that, first, expression (8) shows that the higher harmonics of the fundamental frequency Ω in the voltage spectrum $\dot\Theta$ will be suppressed, because $\Omega \ll 1$. Second, note that voltage $\dot\Theta$ is phase shifted by 90° with respect to signal $M\Omega\cos\Omega t$. Therefore, by detecting the voltage amplitude and phase on the Josephson junction in the experiment, the higher harmonics in the signal spectrum may be suppressed effectively. In this case, the fisrt Shapiro step voltage will contain only the fundamental harmonic Ω:

$$\overline{i} = \omega_0 + M\Omega \cos \Omega t = \omega(t). \quad (9)$$

4. Numerical simulation results

Within the resistive shunted model, numerical solution of equation (1) was also performed using the foyrth-order Runge–Kutta method with the initial condition $\varphi(0) = 0$. The calculations use a finite number of terms $k = 30$ in the sum of series. The signal spectrum and IVC of the Josephson junction are calculated using the fast Fourier transform (FFT) of voltage $U(t)$. FFT is performed after the forced solution of the equation.

Figure 2 shows the IVC calculation of the Josephson junction at different pulse amplitudes a at $M = 0$. It can be seen from Figure 2 that for the Shapiro steps, the synchronization condition $a = 2n\omega_0$ found by us above is fulfilled. In addition, note that, since the current pulse amplitude $a > 0$, the Shapiro steps are observed only at positive shift currents. Voltage spectra on the Josephson junction were also calculated at high modulation coefficients $M = 40$ in pulse-frequency irradiation (Figure 3 and Figure 4). As shown in Figure 3, when shift current is $I = 1$ (corresponding to the center of the Shapiro step), synchronization of the Josephson junction with the external pulsed irradiation is observed and the voltage spectrum contain only the fundamental harmonic of the signal modulation frequency Ω. In case of $I = 2$, the Josephson junction is not synchronized with the external pulsed irradiation and the spectrum contains higher harmonics of the fundamental frequency Ω (Figure 4). Thus, using analytical calculations and numerical simulation within the resistive shunted model,

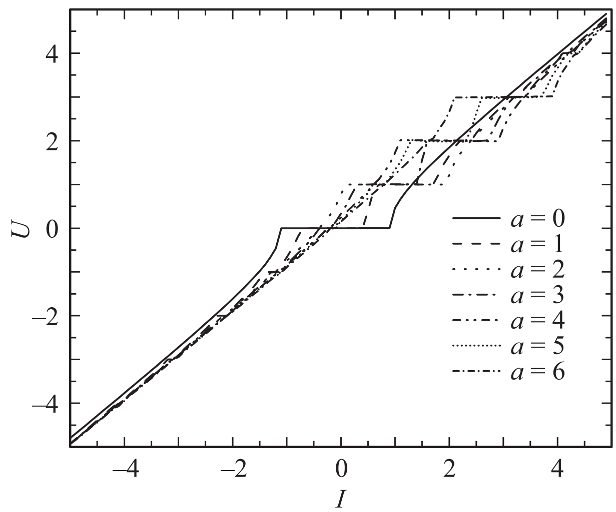

Figure 2. current-voltage curve at pulsed irradiation with various pulse amplitudes a. Modulation coefficient $M = 0$. Pulse repetition rate $\omega_0 = 1$.

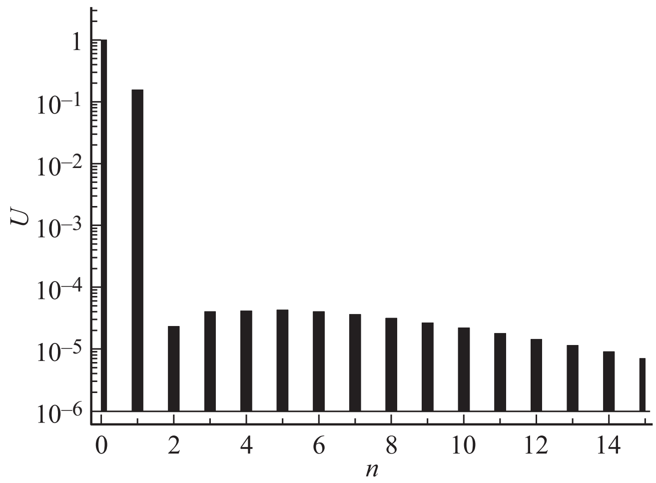

Figure 3. Voltage spectrum of the Josephson junction in pulse-frequency irradiation with shift current $I = 1$ and modulation coefficient $M = 40$ ($\omega_0 = 1$).

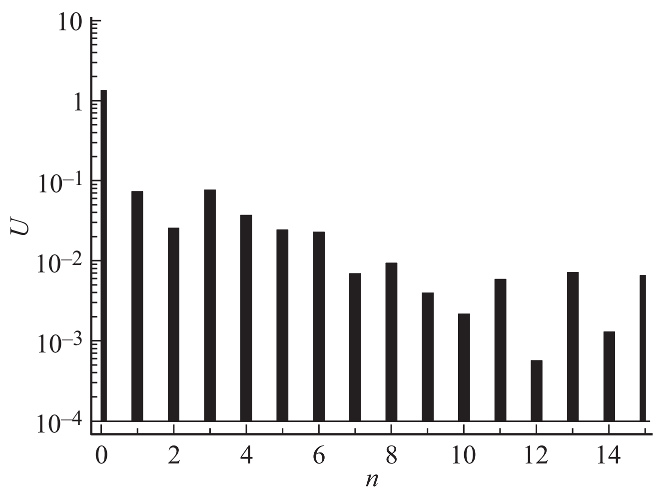

Figure 4. Voltage spectrum of the Josephson junction in pulse-frequency irradiation $I = 2$ and modulation coefficient $M = 40$ ($\omega_0 = 1$).

it has been shown that the Josephson junctions based on high-temperature superconductors may be used to produce an alternating voltage standard.

Finally, it should be noted that, when a Josephson junction array is exposed to current pulsed irradiation, the synthesized signal voltage may be increased by connecting the contacts in series. The future program of study includes experimental investigations of IVC of such structures (Figure 1) exposed to pulse signal and comparison with the results obtained herein.

5. Conclusion

IVC and voltage spectra of the Josephson junction were studied within the resistive shunted model using frequency-modulated pulsed current signal. Conditions of synchronization of the Josephson junctions with the external pulsed irradiation were obtained. It has been shown that the first Shapiro step contains only the fundamental harmonic of the signal modulation frequency. These results can be used to create a quantum alternating voltage generator based on the Josephson junctions made from high-temperature superconductors.

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Conflict of interest

The author declares that he has no conflict of interest.

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