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Citation: Chin. Phys. B . 2019, 28(6): 060305. **doi:** 10.1088/1674-1056/28/6/060305
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Simulation and measurement of millimeter-wave radiation from Josephson junction array*

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(Received 16 January 2019; revised manuscript received 1 April 2019; published online 8 May 2019)

We report the circuit simulations and experiments of millimeter-wave radiation from a high temperature superconducting (HTS) bicrystal Josephson junction (BJJ) array. To study the effects of junction characteristic parameters on radiation properties, new radiation circuit models are proposed in this paper. The series resistively and capacitively shunted junction (RCSJ) models are packaged into a Josephson junction array (JJA) model in the simulation. The current-voltage characteristics (IVCs) curve and radiation peaks are simulated and analyzed by circuit models, which are also observed from the experiment at liquid nitrogen temperature. The experimental radiation linewidth and power are in good agreement with simulated results. The presented circuit models clearly demonstrate that the inconsistency of the JJA will cause a broad linewidth and a low detected power. The junction radiation properties are also investigated at the optimal situation by circuit simulation. The results further confirm that the consistent JJA characteristic parameters can successfully narrow the radiation linewidth and increase the power of junction radiation.

Keywords: high temperature superconducting (HTS) Josephson junction array, radiation, circuit model, simulation

PACS: 03.75.Lm, 74.81.Fa **DOI:** 10.1088/1674-1056/28/6/060305

1. Introduction

In recent decades, the Josephson junction array (JJA) has been widely studied as a radiation source that has an extended frequency, up to terahertz,[1,2] owing to its extraordinary properties, such as low noise, low power consumption, and high sensitivity. If the voltages across all of the junctions are identical, then the JJA will radiate at the Josephson frequency $f = V/N\Phi_0$, where V is the voltage across the whole JJA, N is the number of the active junctions, and Φ_0 is the flux quantum.[3,4] The radiation frequency is accurately related to the voltage across the junction, consequently Josephson junctions (JJs) have practical advantages as high frequency radiation sources. Currently, millimeter waves are commonly applied to the fifth generation (5G) wireless communication, frequency modulated continuous wave (FMCW) radar, medical imaging, *etc*.[5–7] Due to extensive transmission loss of millimeter waves in the atmosphere, it is necessary to study technologies that can implement the JJA with a high radiation power to compensate for the propagation loss.[8]

Much attention has been devoted to investigating the Josephson junction's (JJ's) properties, in terms of both numerical and electromagnetic simulations. Pegrum *et al.*[9] employed the Josephson simulator JSIM to model Josephson mixers. Shukrinov *et al.*[10] observed a devil's staircase structure of subharmonic Shapiro steps using the numerical simulations of the current–voltage characteristics (IVCs) of a Josephson junction under electromagnetic radiation. Rudau *et al.*[11] presented three-dimensional (3D) simulations of the electrothermal properties of an intrinsic Josephson junction stack. However, the research on the effects of JJA parameters on millimeter-wave radiation properties is not yet popular.

The aim of our present work is to design a suitable system to precisely simulate the Josephson junction array radiation. The Advanced Design System (ADS) is a powerful electronic design automation software system that provides an integrated environment to electronic circuit design. In this article, the results of the IVCs and the millimeter-wave radiation peaks of the JJA are obtained by adding the Josephson equations to the circuit model in ADS. The simulated results are compared with the experimental results, which proves the feasibility of the circuit simulations.

*Project supported by the National Natural Science Foundation of China (Grant No. 51002081), the Fundamental Research Funds for the Central Universities, China, the China Manned Space Advance Research Program, China (Grant No. 030201), and the Research Program of Application Foundation and Advanced Technology of Tianjin, China (Grant No. 15JCQNJC01300).

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2. Simulation

A personal simulation program with integrated circuit emphasis (PSPICE) is an electronic circuit design tool that supports users to adopt nodal analysis to construct the circuit equations. In view of no JJ model in ADS, PSPICE code is adapted based on Josephson equations, it then imports it into ADS simulator and considers it as a new circuit element. For direct current (DC) Josephson effect simulations, a well-defined resistively and capacitively shunted junction (RCSJ) model in Fig. 1(a) is used to describe the equivalent circuit of the JJ. In the frame of the RCSJ model, bias current I is defined as[12]

$$I = I_{\rm c}\sin\varphi + C\frac{{\rm d}V}{{\rm d}t} + \frac{V}{R},$$

where $I_{\rm c}$, C, and R, respectively, denote the critical current, capacitance, and normal resistance, V is the voltage across the junction, and φ is the order parameter phase difference. In the simulation of the IVCs curve, the single junction $I_{\rm c}$, C, and R are chosen to be 0.567 mA, 19.224 fF, and 0.137 Ω, respectively, which match those of the experimental values. The characteristic voltage $V_{\rm c} = I_{\rm c}R$ is 0.078 mV and the characteristic frequency $f_{\rm c} = V_{\rm c}/\Phi_0$ is 37.72 GHz. The JJ model is packaged into a unique component with two ports, as shown in Fig. 1(b). In addition, the effect of thermal noise on junction characteristics should be considered because it induces noise-rounding in IVCs above $I_{\rm c}$. To introduce noise into the simulation, pseudo-random sequences are fed to current and voltage utilizing transient simulation.[13] By adjusting noise scale, the strength of thermal noise can be changed, which improves accuracy for exploring influence of thermal noise on dynamic characteristic of the JJ.

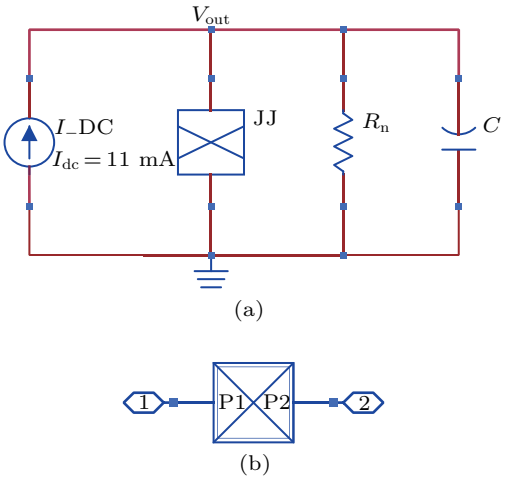


Fig. 1. (a) The RCSJ circuit model of the IVCs simulation. Here, I_DC is the bias current, $R_{\rm n}$ is the total normal resistance, C is the total junction capacitance, and $V_{\rm out}$ is the voltage across the junction. (b) The packaged single RCSJ model without the bias current source.

The primary features of the simulated JJA model containing 528 junctions can be described on the basis of the circuit diagram shown in Fig. 2(a). To reflect the coupling state of the JJA and the external microwave system, the power source is connected to the RCSJ model to provide radiation frequency $f_{\rm RF}$ proportional to the voltage across the junction and a radio frequency (RF) power $P_{\rm RF}$. The $f_{\rm RF}$ applied to the RCSJ model is adjusted to meet the optimum coupling frequency. A series junction array model is packaged and demonstrated in Fig. 2(b). Theoretically, each of the junction arrays has exactly the same characteristic parameters and the Josephson frequency strongly matches that of a cavity resonance. However, in the experiment, the JJA's properties are always limited by the operational process, resulting in a large spread of parameters. So, it is assumed that all the junctions have the same characteristic voltage and the JJA model contains a variety of normal resistance in the simulation.

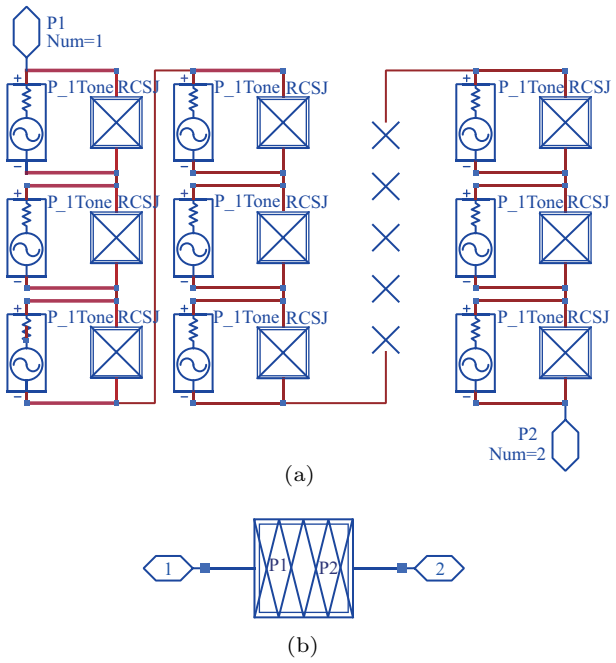


Fig. 2. Schematic diagram of (a) the series RCSJ models with power sources and (b) the packaged JJA model.

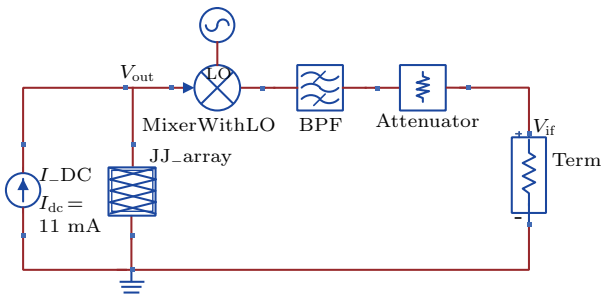


Fig. 3. Equivalent circuit of the millimeter-wave radiation simulation. $V_{\rm out}$ is the voltage across the junction and $V_{\rm if}$ is the IF output voltage.

A JJA can serve as radiation sources according to alternating current (AC) Josephson effect. An electrical diagram is proposed to study the radiation properties of millimeter wave in Fig. 3. The mixer with local oscillator (LO) frequency of 76.3 GHz and conversion gain of 64.5-dB outputs the frequency down-conversion ($f_{\rm IF} = f_{\rm LO} - f_{\rm RF}$) signal via an attenuator which represents microwave link loss. The bandwidth of the bandpass filter (BPF) is 0.1 GHz at the center frequency

of 1.25 GHz. A pin label V_{if} is applied at the intermediate frequency (IF) output port to obtain the IF voltage frequency spectrum. Parameter sweeps of the IF output voltage are carried out against P_{RF} and R. The optimization of the average power is $P_{RF} \sim -15$ dBm and the normal resistances range from 0.122 Ω to 0.148 Ω.

3. Measurement

The BJJ array with 528 junctions is fabricated in $YBa_2Cu_3O_{(7-\delta)}$ (YBCO) thin film forming into a 6-μm wide microbridge with dipole antenna by photolithography and Argon ion etching technologies. The BJJ array is irradiated by microwave of 75.1 GHz at 78 K. The detailed introductions of the measurement system and experimental processes are reported previously.[14–16] Figure 4 shows the schematic diagram of the sample and the radiation measurement system. The microwave radiation signal of the BJJ array is detected in this system.

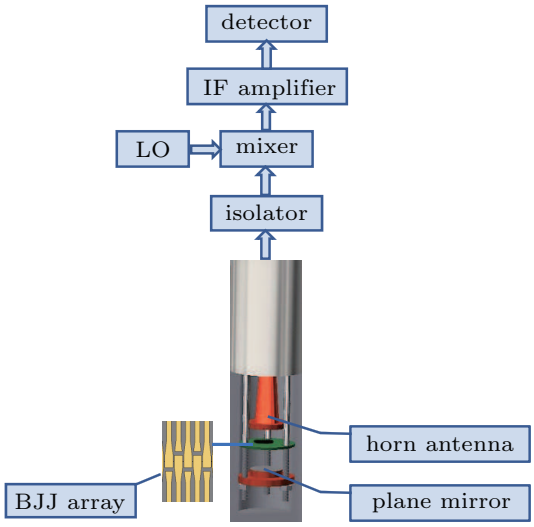


Fig. 4. Schematic diagram of the measurement system.

4. Results and discussion

The IVCs of the JJA are briefly researched without external irradiation. The simulated and measured IVCs curves are both shown in Fig. 5. The critical current is about 0.567 mA and the normal resistance of a single junction is about 0.137 Ω, which are measured at $T \sim 78$ K. The experimental curve is nearly consistent with simulated results. Meanwhile, it obviously displays that thermal noise leads to noise-rounding phenomenon above I_c.

From these circuits, we obtain the simulated results of millimeter-wave radiation under the optimized P_{RF} and R. Figure 6(a) exhibits that the JJA generates a pair of symmetrical radiation peaks at the bias voltage of 81.62 mV, where the maximum IF output voltage is about 115.8 mV. The voltage position of the measured radiation peaks is about 84.45 mV, corresponding to the detected IF voltage of ∼ 112.5 mV, as shown in Fig. 6(b). Note that the voltage linewidth at half maximum of 15.76 mV observed in simulation is slightly different from the measured value of 20.32 mV, which implies that the extra complex disturbance factors exist in the experiment; for example, Joule heat affects the radiation linewidth of the JJA.[17] Considering the gain of IF amplifier (64.5 dB) and the sensitivity of square-law detector (16.4 mV/μW), the extrapolated radiation power is small (pW) for the radiation frequency of 77.3 GHz. The broad radiation linewidth and the low radiation power indicate that not all the junctions achieve phase-locking.[18,19]

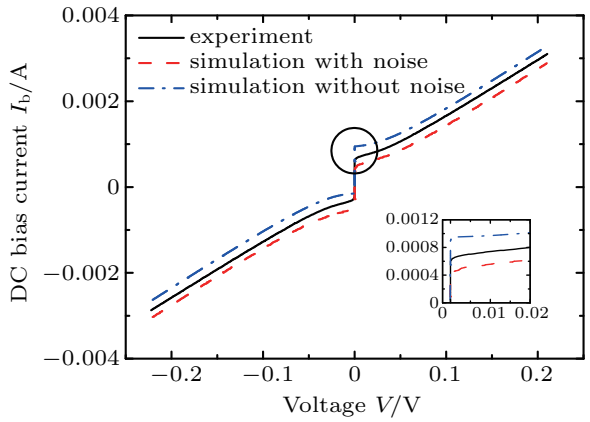


Fig. 5. Results of the IVCs curve. The red dashed line is the simulated I–V curve, the black solid line is the experimental I–V curve whose Y-axis coordinates move up to 0.2 mA, and the blue dash-dot line is the I–V curve without thermal noise whose Y-axis coordinates move up to 0.4 mA. The inset shows an enlarged view of the critical current region.

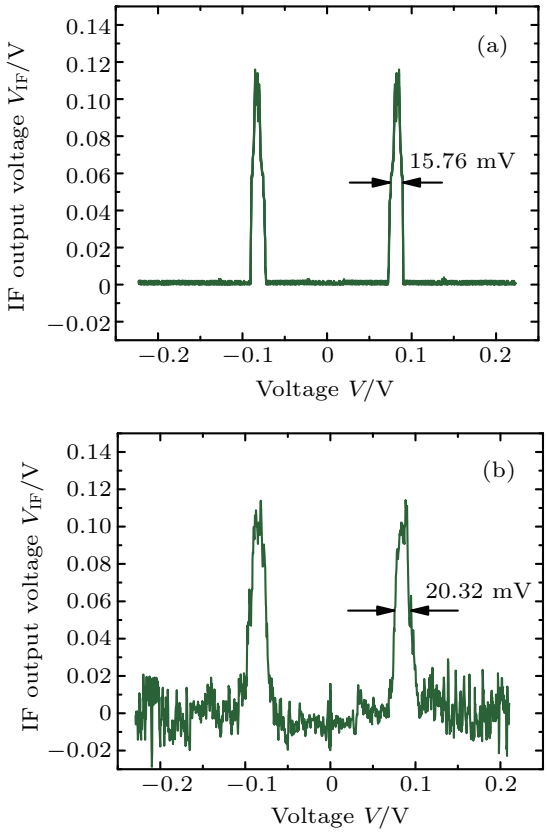


Fig. 6. Plots of the IF output voltage versus the applied bias voltage for the result observed from (a) simulation with the voltage linewidth at half maximum of 15.76 mV and (b) experiment with that of 20.32 mV.

To verify the effects of junction parameters and coupling strength on radiation peaks, the simulation of junction radiation at the optimal situation is further carried out. The packaged JJA model contains the same junctions and the frequency of the connected power source is set to 75.1 GHz, which is consistent with the experiment. The simulated results are displayed in Fig. 7. The radiation linewidth is extremely narrow, and the IF output voltage of ~ 7.88 V at the junction voltage of 82.93 mV is significantly improved, which corroborate the initial prediction. Consequently, we obtain a meaningful clue that the consistent JJA parameters can produce radiation peaks with a narrow linewidth and a high power. The radiation power is affected by junction parameters and coupling effect, which seems to limit the millimeter-wave radiation properties.

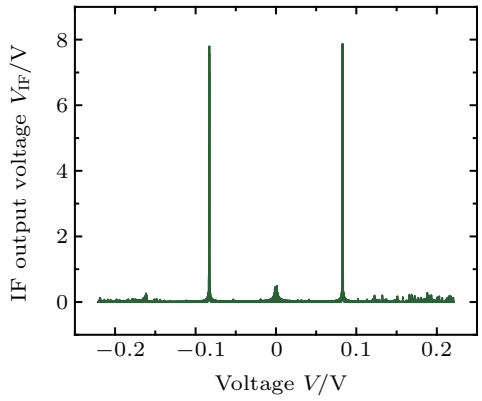


Fig. 7. Plots of the IF output voltage *versus* the applied bias voltage for the result observed at the optimal situation.

5. Conclusions

The simulated and experimental millimeter-wave radiation system of a JJA are established in this paper. The JJA models and radiation circuits are elaborately discussed to analyze the junction radiation properties. Thermal noise factor is effectively added into the circuit models, which provides an improved simulation accuracy for dynamic characteristic. The ADS simulation results show great agreement with experiment ones, including the IVCs curve and radiation peaks of JJA, which means that the experiment is further interpreted by the simulation. The simulated results reveal that inconsistent junction parameters result in a lower power and a boarder linewidth. Although high radiation power is not detected from the BJJ array, the ADS circuit simulations offer a useful method to find the reason for the low power. The consistency of the BJJ arrays needs to be improved by experimental procedure to achieve coherent radiation, hence enhancing the radiation power. In addition, the ADS simulation is suitable for BJJ array as well as some other types of junctions, including intrinsic junctions and step-edge junctions. The simulated and measured results have practical value for exploring JJA as radiation sources in future research.

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