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SIS Junctions with Frequency Dependent Damping for a Programmable Josephson Voltage Standard

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***Abstract*—Experimental and computational results on programmable Josephson junction array (JJA) chips based on superconductor-insulator-superconductor (SIS) junctions are presented. Implications of circuit design and fabrication process on the performance are discussed. We introduce a method to decrease the attenuation of the pump microwave. Different designs are compared, suggesting that 1 V chips operating at the third constant voltage step with 70 GHz pump frequency can be produced with our process.**

***Index Terms*—Josephson arrays, programmable voltage standard, superconductor-insulator-superconductor (SIS) junctions.**

I. INTRODUCTION

TO GENERATE ac voltage with a Josephson voltage standard rapid switching between constant voltage steps is required. This is possible only when the junctions are damped. Programmable Josephson junction arrays (JJAs) are often based on intrinsically damped superconductor-normal conductor-superconductor (SNS) or superconductor-insulator-normal conductor-insulator-superconductor (SINIS) junctions [1], [2]. A problem is the high attenuation of the pump signal, which limits the length of the array branch. It also makes it difficult to use voltage steps $V = nf/K_J$ with $n > 1$. Therefore, longer arrays are needed. In this paper, we present a solution based on externally shunted SIS junctions, which can overcome this problem.

The basic idea is to shunt junctions in a frequency dependent way so that damping is provided at the plasma frequency (typically about 25 GHz) and at lower frequencies to enable rapid transitions between steps but not at the pump frequency. A solution is to use a notch filter at the pump frequency in series with the shunt resistor [3], [4]. This was found, however, too cumbersome to realize. A simpler solution is to use an inductance in series with the resistor. This may degrade the stability of constant voltage steps, so a compromise has to be found.

Based on our earlier studies, we believe that a programmable voltage standard can be used as a precise ac reference at low frequencies at least up to 1 kHz, if the bias system and the signal filtering are optimized [3].

II. CIRCUIT DESIGN AND FABRICATION

The process used in circuit fabrication is modified from the one used in SQUID processing [5]. The conductors are 250 nm to 450 nm thick sputtered niobium layers and the dielectric material is SiO_2 grown with Plasma Enhanced Chemical Vapor Deposition (PECVD) method. The resistor material is molybdenum. The Josephson junctions are Nb/Al/AlO_x/Nb-sandwiches bounded with Nb_2O_5 formed by anodization. By varying the oxidization pressure, critical current densities from 10 A/cm^2 to 100 A/cm^2 have been obtained. With the junction size of (20 μm) $\times$ (50 μm) critical currents can be varied from 100 μA to 1000 μA.

III. EXPERIMENTAL RESULTS

The design of the test components is shown in Fig. 1(a). The junctions on different wafers had critical currents of about 100 μA, 200 μA, and 800 μA. The capacitance is about 45 pF and the shunt resistance is about 0.25 Ω. The junctions form a microstripline and they are connected to the resistors via Nb strips. The strips and the resistor have an inductance of about 3 pH per junction.

The measurements with one or a few series connected junctions showed that stable constant voltage steps were obtained for components having $I_c \lesssim 200$ μA. The step amplitudes also followed the Bessel-function dependence $\Delta I_n = 2I_c|J_n(AI_1)|$, where I_1 is proportional to the pump current and A is a constant depending on the shunt impedance and the frequency. The components with $I_c \approx 800$ μA, showed voltage steps, the amplitudes of which were suppressed with small pump amplitudes. With larger amplitudes stable steps were obtained also in this case. The measurements with arrays having a larger number of junctions showed, however, that the voltage steps are rounded (Fig. 2).

To determine the attenuation of the pump signal, the step amplitudes of the first and last junctions in a series of 260 junctions were measured as a function of the input pump power. The result was fitted to the function $\Delta I_n = 2I_c|J_n(B\sqrt{P_{\mathrm{in}}})|$. The attenuation was then determined from the ratio of constants B for the first and the last junction. An example of the measured step amplitudes is shown in Fig. 3(a) for a shunted array and in Fig. 3(b) for an unshunted array. The attenuation of the former varied between 13 dB and 14 dB, i.e., about 0.05 dB per junction (15 dB/cm). For the latter, it was between 2.3 dB and 2.7 dB, i.e., about 0.01 dB per junction (3 dB/cm).The damping of a shunted 308 junction branch is therefore about 15 dB, which explains the rounding of the steps.

IV. LINEAR CIRCUIT MODEL

To study the pump attenuation, a linear model was constructed, as shown in Fig. 4(a). The circuit simulation software

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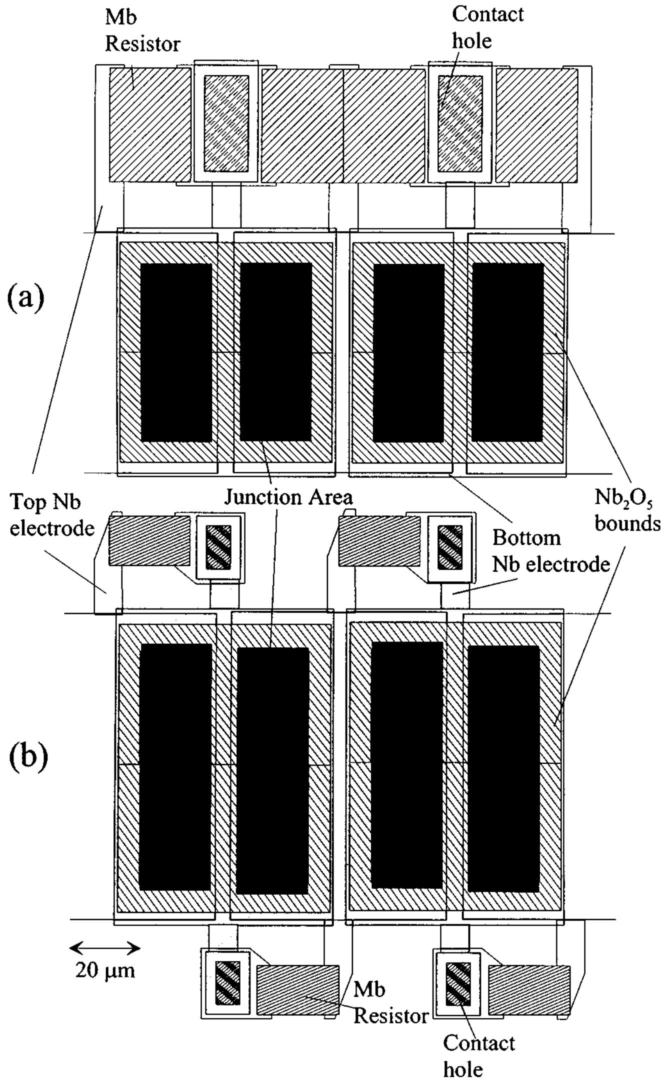

Fig. 1. Piece of microstripline including Josephson junctions. (a) Design of test structures. Parameters: $I_c = (100 - 800)\ \mu$A, $C = 45$ pF, $R = 0.25\ \Omega$, $L = 3$ pH. (b) Design used to minimize the pump microwave attenuation. $I_c = (200 - 500)\ \mu$A, $C = 63$ pF, $R = 0.31\ \Omega$, $L = 4$ pH. For both (a) and (b) the dielectric thickness of the microstripline is about 1 μm.

Aplac was used to compute the propagating amplitude at different points of the transmission line. The Josephson junctions were described as capacitors and the Josephson coupling was neglected in this analysis. The transmission line sections were described with the built-in model of Aplac. The model of [6] was used in calculating the parameters of superconducting microstriplines. In Fig. 5(a) it is shown the voltage amplitude against the ground plane at the first and last junctions computed with the parameters of the system of Fig. 4(a). The resulting attenuation is then found to be about 13 dB, which is in good agreement with the measured value (about 12 dB excluding the attenuation independent of the shunt circuits).

V. DECREASING THE ATTENUATION

An alternative design is shown in Fig. 1(b). The linearized model of it is shown in Fig. 4(b). The most important difference is that the shunts of sequential junctions are at the opposite sides of the microstripline. With this arrangement the shunt resistors do not form a transmission line, and the series inductance blocks the pump signal from the resistor more efficiently. It was also found essential to maximize Z_2/Z_0 in Fig. 4(b). Making the resistor narrower by decreasing the sheet resistance of molybdenum increases Z_2. Increasing the width of the junction decreases Z_0.

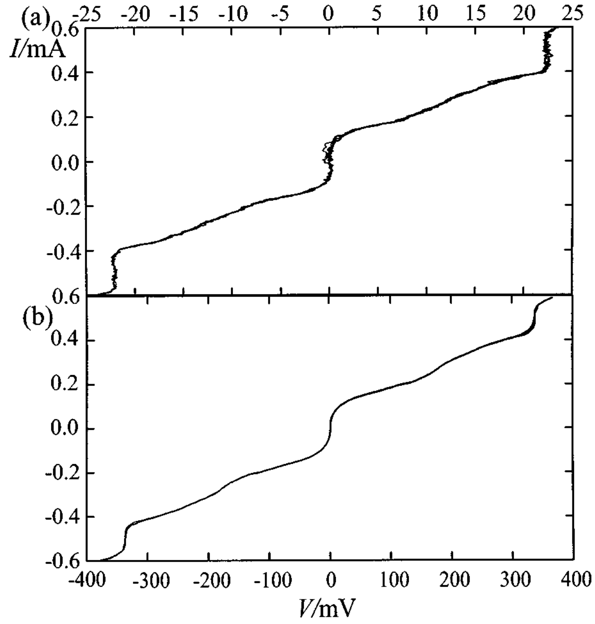

Fig. 2. Current–voltage characteristics with 70 GHz pump. (a) Branch of 154 junctions. (b) 2310 junctions divided in eight branches.

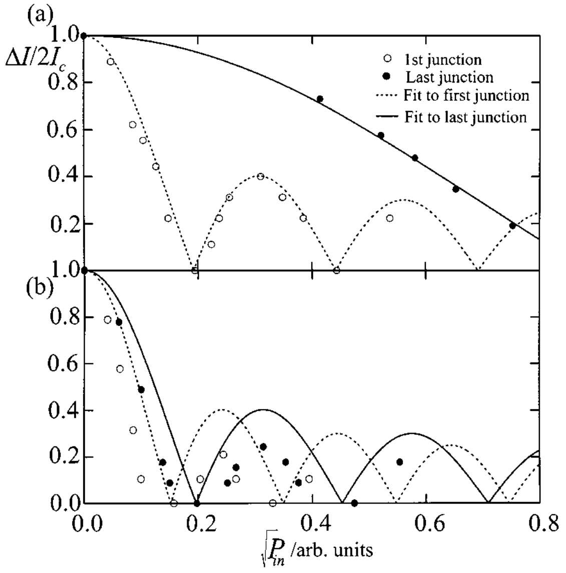

Fig. 3. Amplitudes of the zeroth constant voltage steps as a function of pump power for (a) shunted array branch and (b) unshunted array branch. Both have 260 junctions. According to the Bessel fit the attenuation of the line is about 0.05 dB per junction in (a) and 0.01 dB per junction in (b). In (b), the step amplitudes are suppressed from the theoretical values probably due to the external noise.

The resulting voltage amplitudes at different junctions in an array branch of 154 junctions are shown in Fig. 5(b). Owing to the extra circuits the characteristic impedance of the transmission line is frequency-dependent. By varying the input and

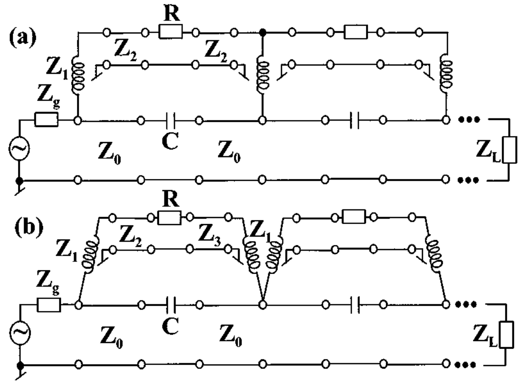

Fig. 4. Linearized models used in pump attenuation computation. (a) The circuit of Fig. 1(a). The parameters used in analysis are $Z_0 = 2.6\ \Omega$, $Z_1 = 17.2\ \Omega$, $Z_2 = 6.0\ \Omega$, $C = 45$ pF, $R = 0.25\ \Omega$ and $Z_g = Z_L = 2.6\ \Omega$. (b) The circuit of Fig. 1(b). The parameters are $Z_0 = 2.0\ \Omega$, $Z_1 = 17.2\ \Omega$, $Z_2 = 13.5\ \Omega$, $Z_3 = 7.3\ \Omega$, $C = 63$ pF, $R = 0.31\ \Omega$ and $Z_g = Z_L = 1.6\ \Omega$. The strips connecting the junctions and shunts are drawn as inductors for clarity, but they are also modeled as microstriplines.

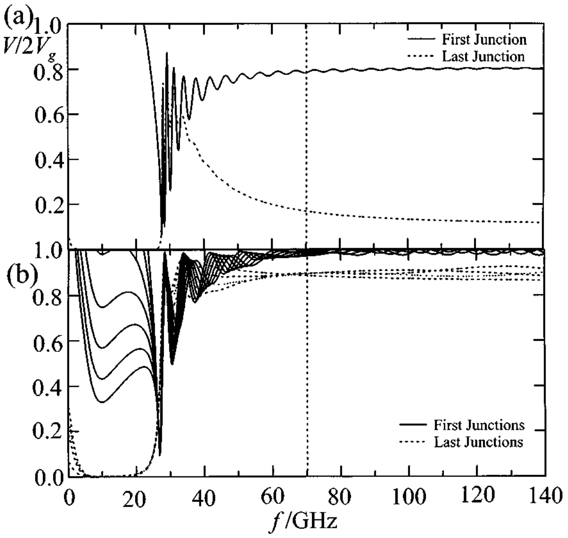

Fig. 5. The propagating amplitude at the beginning and the end of a transmission line. (a) Model 4(a), 308 junctions. (b) Model 4(b), 154 junctions. In (b), the voltage at different points of the transmission line is shown. The ripple indicates standing wave, which has been minimized at 70 GHz.

output impedances $Z_g = Z_L$, an optimum was found and thus no standing wave occurs at 70 GHz. The attenuation due to shunt resistors is then found to be about 1.0 dB for 154 junctions. If the shunt-independent part of the attenuation is 0.01 dB per junction (the measured value), the total attenuation of 154 junctions is about 2.5 dB and 218 junctions about 3.6 dB. Using 15 branches of 154 (218) junctions the output voltage is 1.00 V (1.42 V) if the pump frequency is 70 GHz.

We suppose that the pump attenuation in the unshunted circuits follows mainly from the dielectric loss of the microstripline. PECVD SiO_2 layers deposited at low temperatures can contain up to a few percent hydrogen. Vibrational modes of Si-H bonds are known to produce strong absorption bands in the infrared regime. They are also likely to cause excess losses at microwave frequencies. Processing SiO_2 at a higher temperature may therefore decrease the attenuation.

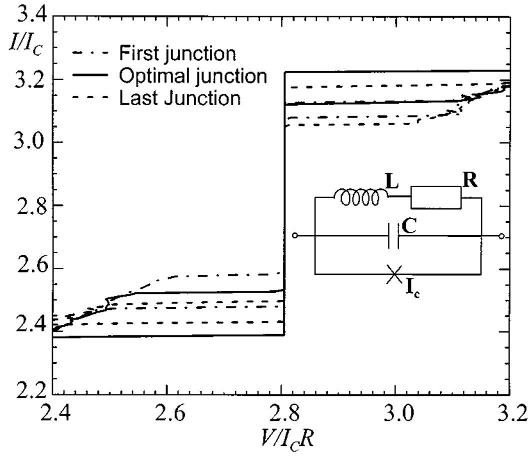

Fig. 6. Simulated I–V curves of junctions at different positions of the transmission line, when its total attenuation is 3.6 dB. The junction is described with the lumped model shown in the inset, the parameters of which are those given in Fig. 1(b). Here $I_c = 500\ \mu$A. The effective step amplitude without the resistance scatter is found to be about $0.4I_c = 200\ \mu$A.

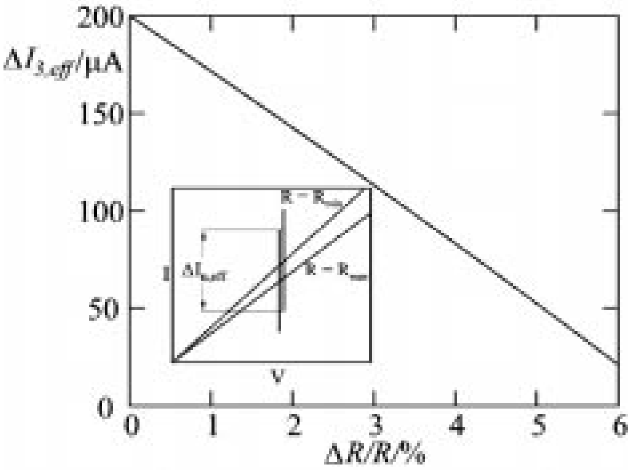

Fig. 7. Effective step amplitude of the third step as a function of resistance scatter. It is assumed that $R = 0.31\ \Omega$, $\Delta I_{3,0} = 200\ \mu$A, and $V_0 = 434\ \mu$V in (1).

VI. SIMULATIONS

To find the I–V curve of the system, simulations including the nonlinear effects were executed. The lumped model is shown in the inset of Fig. 6. The value $L = 4$ pH was found by fitting the impedance parallel to the Josephson tunnel element to the value obtained numerically from the linearized model of Fig. 4(b). The effective amplitude $\Delta I_{n,\mathrm{eff}}$ of the nth constant voltage step is defined so that all the junctions in the array are biased at the step simultaneously, if the bias current $I_b = I_m \pm (1/2)\Delta I_{n,\mathrm{eff}}$. Here $I_m = (nf)/(K_J R)$ is the center of the step. The amplitude depends on the critical current, the attenuation and the resistance scatter. Also hysteresis decreases $\Delta I_{n,\mathrm{eff}}$, since a junction may be at the resistive branch of the I–V curve if it is biased so that the voltage is not unambiguous. In Fig. 6 it is shown an I–V curve of the third voltage step for different junctions in the same junction branch assuming that the attenuation is 3.6 dB. It is shown that the step amplitude is in this case $0.4I_c \approx 200\ \mu$A. To include the resistance scatter, simple geometrical analysis (see inset of Fig. 7) shows that the effective amplitude is obtained from

$$\Delta I_{n,\,\mathrm{eff}} = \Delta I_{n,\,0} - \frac{2V_0 \Delta R}{R^2} \tag{1}$$

where V_0 is the voltage of the step (in this case about 434 μV) and $\Delta I_{n,\,0}$ is the amplitude if the scatter is zero. The error is defined as $\Delta R = (R_{\max} - R_{\min})/2$. Fig. 7 shows $\Delta I_{3,\,\mathrm{eff}}$ as a function of $\Delta R/R$ in this case.

Too large a critical current or an inductance may destroy the stability of constant voltage steps. To find tolerances for the design, simulations with $L = 4$ pH and different values of I_c were executed. Stable constant voltage steps appeared at least if $I_c \lesssim 1$ mA. To estimate the effect of inductance, simulations with $I_c = 500$ μA were executed as a function of L. Stable steps were obtained at least if $L \lesssim 20$ pH.

VII. CONCLUSIONS

We have shown that with appropriate circuit design and fabrication it is possible to realize a programmable voltage standard based on SIS junctions, which works at the third constant voltage step with 70 GHz pump frequency. With the linearized model,we were able to predict the measured attenuation caused by the shunt circuits. A proper way to damp junctions frequency-dependently was found to enable both rapid switching between constant voltage steps and low pump signal attenuation.

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