

The Influence of the Resonator on the Self Heating Effect and the Synchronization of Josephson Junctions

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Abstract - Arrays of synchronized Josephson junctions can be used as coherent frequency sources where the voltage across the junctions is connected to the frequency only via fundamental constants. Recent results on intrinsic Josephson junctions in high temperature superconductors show problems with synchronization and self-heating effects. Thus we investigate numerically the temperature of the self-heated chain of two current-biased Josephson junctions loaded by a resonator and the conditions of synchronization in the system. For calculations we used parameters of intrinsic Josephson junctions in high temperature superconductors. We found that the increase of the ac current at the resonant frequency results in the phase locking of junctions (coherent radiation) as well as in an increase of the temperature of each of the junctions above the nominal bath temperature of the cryostat. Both the increase of the temperature and the phase locking appear in the same interval of the bias currents.

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I. INTRODUCTION

The problems connected to the use of Josephson junctions as tunable sub-mm oscillators with a high precision of frequency become important because of the application of the sub-mm wave band sources in different fields of science. The main problem of Josephson junction oscillators is the phase locking of many junctions to get appreciable large output power. An easy way to solve this problem is to use a resonator to perform a phase locking feedback. Recently, immense progress in experiments on the detection of synchronized radiation from intrinsic Josephson junction arrays in high temperature superconductors (HTSC) was achieved [1-3]. The main idea of these experiments was to use the stack itself as a geometrical resonator. However, in this case layers of junctions are placed in the nonuniform electromagnetic field which forms the standing wave inside the stack. Due to this design, some areas of the same layer appear in almost zero fields that make them insensible to synchronization, and other areas are placed at the maximum of the standing wave. Hot spots were observed in these places of maxima of electric field [3]. The stacks emit radiation coherently at the input power which provides the formation of both a hot spot and a standing wave in the stack.

In the present paper we concentrate on the origin of the correlation between overheating of some areas of the stack and the formation of the coherent radiation from this area. We consider the problem of the self-heating of some line of junctions in the macroscopic resonator. This is the straightforward modeling of a hot spot, *i.e.* the line represents some spatial place in the large self-resonating stack where the excited electric field has the maximal amplitude. We obtain the interval of bias current at which synchronization of junctions is possible, calculate the temperature of the junctions in the chain and discuss the connection between synchronization and the overheating. Note that in the stack there exist also the ‘cold spots’ which spatially are placed near zero points of the excited standing wave in the resonating stack and can be modeled as lines of junctions without any feedback.

II. THE MODEL

The equations of phase dynamics for the line of two junctions connected with a resonator read as follows:

$$C_i \frac{\Phi_0}{2\pi} \frac{d^2 \varphi_i}{dt^2} + \frac{\Phi_0}{2\pi R_{Ji}} \frac{d\varphi_i}{dt} + I_{ci} \sin(\varphi_i) + \frac{dq}{dt} = I_b, \quad i = 1, 2, \quad (1a)$$

$$L \frac{d^2 q}{dt^2} + R \frac{dq}{dt} + \frac{q}{C} = \frac{\Phi_0}{2\pi} \left(\frac{d\varphi_1}{dt} + \frac{d\varphi_2}{dt} \right) \quad (1b)$$

where φ_i is the phase difference across the i -th junction, I_{ci} , C_i and R_{Ji} are the critical current, the capacitance and the resistance of the i -th junction, correspondingly; L , C and R are the capacitance, the inductance and the resistance of the resonant contour, q is the charge on the capacitor C , I_b is the bias current, t is the time and $\Phi_0 = 2.07 \cdot 10^{-15}$ Wb is the quantum of magnetic flux. Resistances of junctions were chosen to satisfy the equality of critical voltages $V_{c1} = V_{c2}$ at T_{cr} as the bath temperature of the cryostat.

In the simplest model of the self-heating, the temperature of the overheating is proportional to the averaged power of the junction [4], so for the i -th junction ($i = 1, 2$) one obtains:

$$\Delta T_i = \gamma_i \langle I_i^2 \rangle R_{Ji}, \quad (2)$$

where $\Delta T_i = T_i - T_{cr}$ with T_i as the temperature of the i -th junction, $\langle I_i^2 \rangle$ is the averaged on time square of the current flowing through the junction, $\gamma_i \approx \frac{1}{2\pi\lambda r}$ is the coefficient which characterizes the heat sink [4] with λ as thermal conductivity of the high temperature superconductor and r as the radius of the hot spot. We chose $\lambda = 7$ W/(m·K) [6] and $r = 50$ micrometers [2]. We suppose also $\gamma_1 = \gamma_2 = \gamma$ for simplicity. Close to the critical

temperature T_c , the temperature dependence of characteristic voltage $V_{ci} = I_{ci}R_{ji}$ can be expanded to the first order [4]:

$$V_{ci}(T_i) = V_{ci}(T_{cr}) + \frac{dV_c}{dT}(T_i - T_{cr}). \quad (3)$$

Supposing $R_{ji}(T) \approx const.$, for HTSC we can use the measured dependence $I_c(T)$ and obtain $\left| \frac{dV_c}{dT} \right| \approx 1.63 \cdot 10^{-4}$ V/K [5]. Then from Eqs. (2) and (3), one obtains:

$$V_{ci}(T_i) = V_{ci}(T_{cr}) - \gamma \left| \frac{dV_c}{dT} \right| \langle I_i^2 \rangle R_{ji}.$$

(4)

With the use of Eqs. (1a), (1b) and (4) we can find IV -characteristics of junctions and from Eq. (2) we find the temperatures of the junctions at each bias current.

III: RESULTS AND DISCUSSION

Calculated IV -characteristics of junctions in the resonator are shown in Fig. 1a. The region of bias currents where voltages over junctions have the same values is marked in Figure 1(a) by ΔI . Another interval at $I_b/I_{c2}(T_{cr}) \leq 0.6$ we will not consider because it has the very small amplitudes of the ac current (though all considered effects are valid for this case too). Phases of junctions are locked at these bias currents, so ΔI is the so-called locking interval. The locking interval can also be shown as ranges of the maximum of the ac power, see inset in Fig. 1(a). The origin of these phase-locked states is a strong ac current in the resonance circuit.

In the region of the resonant frequency the temperature of the overheating ΔT_1 increases sharply (Figure 1b). Ranges of the increase of ΔT_1 coincide with ranges of ΔI shown in Fig. 1a. The origin of the increase of the temperature is again the increase of the current flowing through the resonator. Thus, we have shown that the resonator itself can increase the working temperature of the radiating junctions. The origin of this effect is demonstrated but the real process will be more difficult including spatial distribution of heat, resonant heat oscillations, complex local interactions of junctions as well as additional thermal noise. We considered the chain of two separated junctions, while intrinsic Josephson junctions placed very close to each other, so Joule losses from each of the junctions should be added and the overheat is doubled. Using data of Fig. 1b we can see that for the chain of 660 junctions [2] the temperature can increase above the critical temperature if the chain is loaded by the resonator while for the unloaded chain the temperature increases only on about 30 K for the same bias current $I_b = 1.2I_{c2}$.

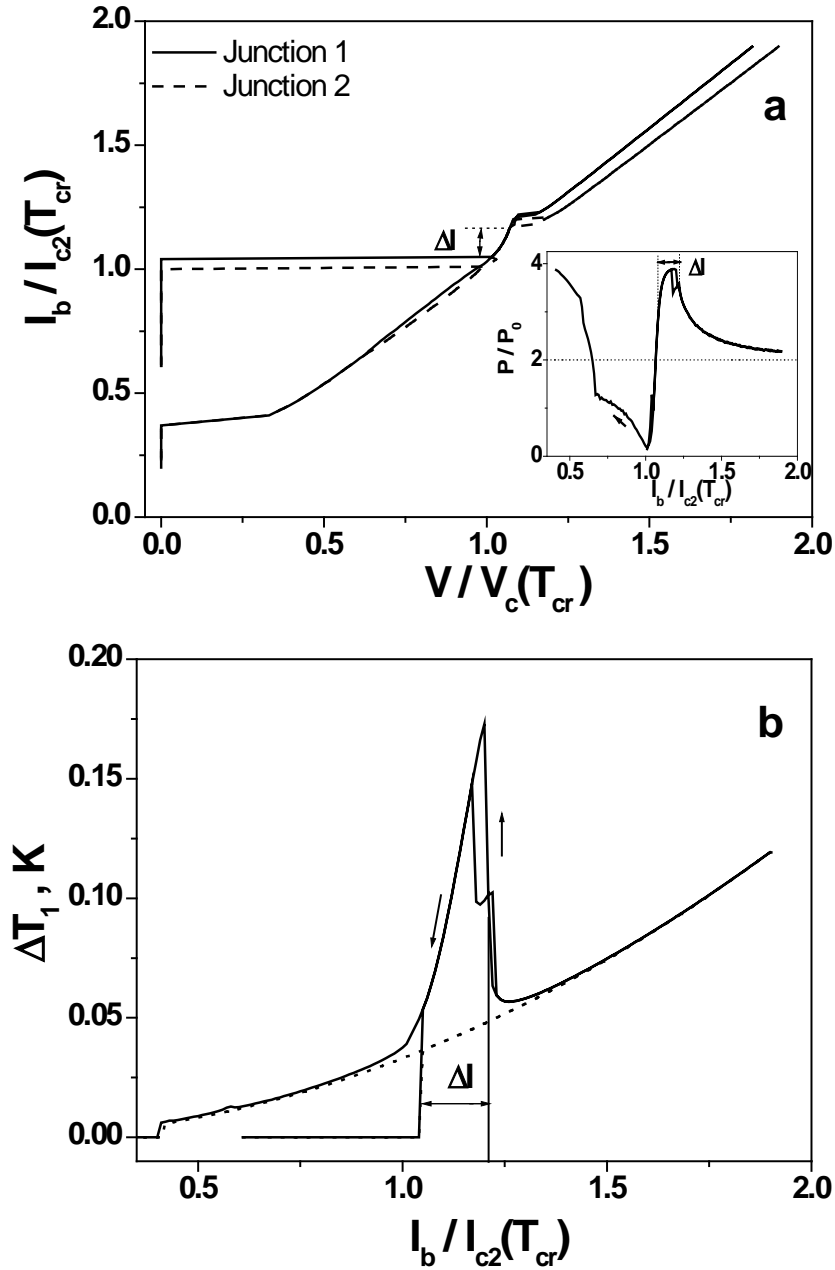


Fig. 1. (a) IV-characteristics of two self-heated Josephson junctions in the resonator.

Parameters of the system: $I_{c1}=14.1$ mA, $I_{c2}=13.5$ mA, $R_{J2}=0.5$ Ohm,

$$\beta_C = \frac{2\pi I_{c2} R_{J2}^2 C_{1,2}}{\Phi_0} = 10, \quad \beta_{Cres} = \frac{2\pi I_{c2} R_{J2}^2 C}{\Phi_0} = 1, \quad \beta_L = \frac{2\pi I_{c2} L}{\Phi_0} = 1,$$

$R=0.02$ Ohm, $\gamma \left| \frac{dV_c}{dT} \right| = 0.062$ A⁻¹. The locking interval ΔI is marked. In inset: the

dependence P/P_0 on the normalized bias current. Dotted line $P/P_0=2$ denotes the absence of the synchronization. (b) Dependence $\Delta T_1 = f(I_b/I_{c2}(T_{cr}))$ for the chain of junctions with the resonator (solid line) and without the resonator (dotted line). The direction of the movement of the current is shown by arrows. The locking interval ΔI is marked.

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