

Tunable phase locking of stacked Josephson flux-flow oscillators

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A tuning technique for mutual phase locking of two vertically stacked long Josephson junctions is suggested and successfully tested. The technique is based on passing a current through the middle electrode between two tunnel barriers. Mutually synchronized oscillation modes in the Nb/Al–AlO_x/Nb stack are found to be tunable in the frequency range from 180 to 420 GHz. Presented results extend the possibility of using stacked long Josephson junctions as coherently operating oscillators for millimeter and submillimeter wave bands. © 1996 American Institute of Physics. [S0003-6951(96)00402-9]

By applying a current and an external magnetic field to a long Josephson junction (JJ) one can induce moving flux quanta in the junction. This motion leads to the Josephson radiation and appears as the so-called flux-flow step on a current–voltage characteristic (I – VC) of JJ. Recently, long JJs operating in the flux-flow mode showed very promising performance as local oscillators in integrated submillimeter wave band superconducting receivers.¹

Here we investigate experimentally the dynamics of two stacked long JJs operated in the flux-flow mode. Numerical simulations by Petraglia *et al.*² showed that, due to inductive coupling between the junctions, the motion of fluxons in different junctions of the stack can be mutually synchronized. First, an experimental demonstration of such a coherent motion has been accomplished using stacks with junctions of nearly identical parameters.³ In practice, however, it is rather difficult to fabricate stacked JJs with equal parameters, especially to precisely control the thicknesses of the tunnel barrier t and superconducting electrodes. In this letter, we suggest a technique which is allowed to tune the Josephson double junction stack to a mutually synchronized state, even if the spread in the fluxon density is as large as 100%.

For a system of two stacked JJs numerical simulations² predict two kinds of mutually synchronized flux-flow states with either in-phase or out-of-phase Josephson oscillations in two junctions. The out-of-phase locking is characterized by the velocity \bar{c}_- and it naturally appears in statics due to the repulsion between fluxons of the same polarity which force them to take alternating positions in neighboring junctions. The out-of-phase synchronization is typically observed for $d_m \approx \lambda_L$, i.e., at a moderate inductive coupling strength. In its turn, the in-phase locking characterized by the velocity \bar{c}_+ is essentially a dynamic phenomenon⁴ and is only found at higher fluxon velocities. Both locking modes can be useful for oscillator applications: the in-phase mode is expected to double the power and reduce the radiation linewidth, while the out-of-phase mode doubles the radiation frequency emitted into a common transmission line. Such frequency doubling can be useful in order to overcome the gap frequency limit of operation of a single layer flux-flow oscillator.

For the tunable phase-locking experiment we used the sample geometry schematically shown in Fig. 1(a). This stacked structure consists of two long JJs with the lower and the upper electrodes of the overlap geometry and with the middle electrode furnished with in-line extensions at the sides. Bias current I is applied from the lower to the upper electrode. An additional tuning current I_H is fed through the middle superconducting electrode between two JJs A and B. The voltages on JJs are measured separately, as shown in Fig. 1(b). The external magnetic field H is applied parallel to tunnel barriers and perpendicular to the larger dimension of the JJs. Experiments were accomplished at 4.2 K using stacked Nb/Al–AlO_x/Nb Josephson junctions fabricated at KFA Jülich. The details about the sample fabrication are described elsewhere.⁵ To provide sufficient inductive coupling between the junctions we used the middle electrode of the thickness $d_m = 90$ nm, which is close to the London penetration depth λ_L of our sputtered Nb films. In order to overcome

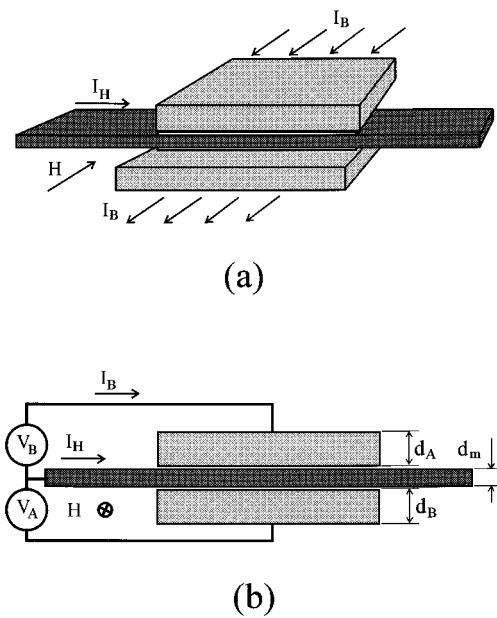


FIG. 1. (a) Sketch of a two-fold long Josephson junction stack with extensions of the middle electrode, (b) cross section of the structure in the plane perpendicular to the tunnel barrier. Vertical dimensions are not to scale.

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a steep edge step of the lower Nb layer we used a simple planarization process.⁵ Within the accuracy of photolithographic alignment (better than 1 μm), the fabricated devices had the same area of $L \times W = 100 \times 10 \mu\text{m}^2$ for the top and bottom JJs. The Josephson penetration depth λ_J was about 25 μm at 4.2 K.

By applying the magnetic field H one introduces the magnetic flux of the same polarity in both junctions. At the same time, the tuning current I_H flowing through the middle electrodes induces magnetic fluxes of the opposite polarities. In the experiment, due to the difference in parameters (for example, different electrode thicknesses d_A and d_B , or different critical currents) the magnetic field H creates different magnetic flux densities, the junctions A and B. This asymmetry can be compensated by the current I_H of appropriate direction. Thus, both JJs can be tuned to the same density of magnetic flux which is an essential condition for their mutual synchronization. The asymptotic flux-flow voltages V_{FF} can be written as

$$\begin{aligned} V_{\text{FF}}^A &= \bar{c}_A^* (\Lambda_A H + k_A I_H), \\ V_{\text{FF}}^B &= \bar{c}_B^* (\Lambda_B H + k_B I_H), \end{aligned} \quad (1)$$

where $\Lambda_{A,B} = t_{A,B} + \lambda_L [\tanh(d_{A,B}/2\lambda_L) + \tanh(d_m/2\lambda_L)]$ are the effective magnetic field penetration depths of the JJs, $k_A > 0$ and $k_B > 0$ are geometry dependent constants defining the influence of the current I_H on each junction, $\bar{c}_{A,B}^*$ are the characteristic velocities (Swihart velocities) of the electromagnetic waves propagation in each JJ. According to the theory^{2,4} and previously reported experiments,⁶ in a double junction stack the velocity \bar{c}^* splits in two values due to the splitting of the dispersion relation in two mutually coupled Josephson transmission lines. The lower velocity value, \bar{c}_- , corresponds to the out-of-phase wave propagation mode in two JJs. The upper velocity, \bar{c}_+ , corresponds to the in-phase mode. For a mutually phase-locked state, the Josephson generation takes place if the conditions $V_{\text{FF}}^A = V_{\text{FF}}^B$ and $\bar{c}_A^* = \bar{c}_B^* = \bar{c}^*$ (\bar{c}^* should be equal to either \bar{c}_+ or \bar{c}_-) are satisfied for given $\Lambda_{A,B}$ and $k_{A,B}$. These requirements can be satisfied by the appropriate choice of H and I_H .

The dependence of critical current I_c on magnetic field H for the top and bottom junctions at $I_H = 0$ is shown in Fig. 2. The current I was applied through the whole stack and the voltages were detected individually on each JJ as shown in Fig. 1(b). Typically for long JJs (in our case $L/\lambda_J \approx 4$), both JJs show an approximately linear decrease of I_c at small field H . One can see that the curves $I_c^A(H)$ and $I_c^B(H)$ differ from each other. However, there is a region near the origin where $I_c^A(H)$ and $I_c^B(H)$ coincide. Such a behavior in stacked JJs has been reported earlier⁷⁻⁹ and is called the current locking. It possibly results from the inductive interaction between the top and bottom JJs. Switching of one junction to a resistive state triggers the vortex motion which compels the fluxons in the other junction to move as well. From Fig. 2, one can see that the ratio of the first critical fields H_{c1}^A/H_{c1}^B of the JJs is about 2.5. Calculation of this ratio using the approach with inductive coupling between JJs yields $H_{c1}^A/H_{c1}^B = (\Lambda_B - s_1)\lambda_J^B/\Lambda_A\lambda_J^A \approx 2.3$, where s_1 is the coupling constant.¹⁰

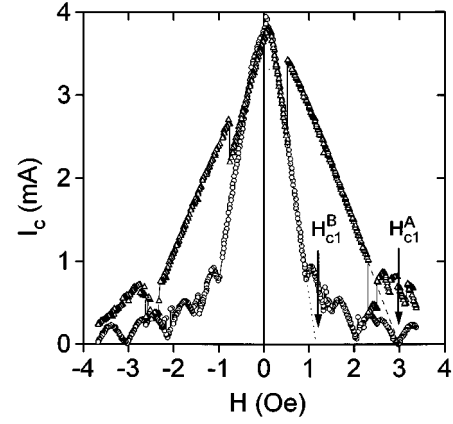


FIG. 2. Experimentally measured dependence of the critical currents of two stacked junctions I_c^A and I_c^B on the applied magnetic field H at $I_H = 0$.

Several $I_c^A(H)$ curves measured at different values of the current I_H passing through the middle electrode, are shown in Fig. 3. With increasing I_H , the peak around $H=0$ is destroyed and another peak of I_c^A appears at $H > 0$ which corresponds to the shift of the virtual zero field H_0^A (indicated by arrows) for junction A. One may expect the rate of $dH_0^A/dI_H \propto k_A/\Lambda_A$. Similar behavior has been observed for junction B, but the peak I_c^B shifted towards negative H with the slower rate. Comparing two rates dH_0^A/dI_H and dH_0^B/dI_H , we calculate the ratio $\Lambda_B k_A/\Lambda_A k_B$ which appears to be about 2.2. Taking into account the ratio $\Lambda_A/\Lambda_B = 0.7$ calculated from the layer thicknesses, one gets $k_A/k_B = 1.5$. This ratio characterizes the difference of magnetic fluxes introduced by current I_H in two JJs.

When increasing H from zero, Fiske steps first appeared only in the $I-V$ of the junction A, and with further increase of H the steps also appeared in the junction B. At $I_H = 0$ the voltages of the highest steps V_{FF}^A and V_{FF}^B were different by a factor of about 2 and no mutual synchronization between JJs was found. In order to lock the flux-flow modes of two junctions at fixed H , we tuned I_H to a value that was sufficient to compensate the magnetic flux density difference between the junctions. In a narrow interval of I_H this resulted in appear-

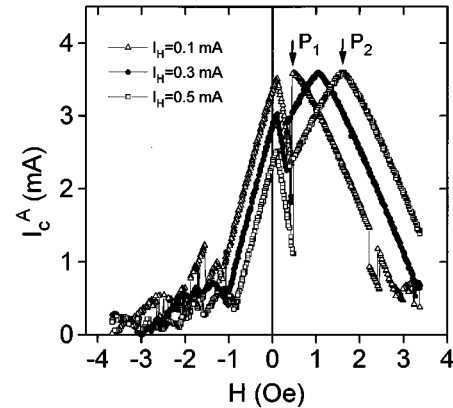


FIG. 3. Critical current of junction A I_c^A vs H taken at I_H values indicated on the plot. The arrows P1 and P2 show the positions of the maximum of I_c^A at $I_H = 0.1$ mA and $I_H = 0.5$ mA, respectively.

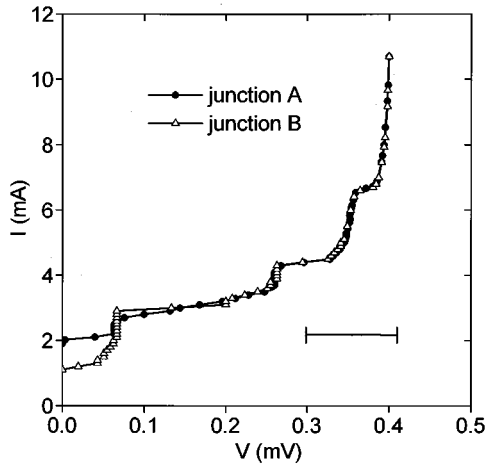


FIG. 4. Current–voltage characteristics of two JJs measured simultaneously in a synchronized state. The bar shows the voltage locking range of two junctions.

ance of flux-flow branches at equal voltages in both junctions (within the accuracy of our measurements of about $1 \mu\text{V}$). These mutually synchronized flux-flow branches were manifested by their large current amplitude which often was by factor of about 2 larger than the maximum current height of nonsynchronized steps. When increasing the bias current I , both JJs were switching to and from such branches simultaneously. By adjusting I_H , we were able to obtain synchronized flux-flow steps in broad range of magnetic field H , from 2.2 to 7.2 Oe. An example of mutually synchronized flux-flow state is shown in Fig. 4.

Our data show, that even in case of $\Lambda_A \neq \Lambda_B$, the appropriate choice of H and I_H allows to satisfy the condition $V_{\text{FF}}^A = V_{\text{FF}}^B = V_{\text{PL}}$ for a broad range of V_{PH} values. We measured the synchronized states at different I_H values, by adjusting the magnetic field H at every point. The dependence $V_{\text{PL}}(I_H)$ shown in Fig. 5 displays is staircaselike profile due to the predominant locking of flux flow motion to the Fiske resonances. In general, V_{PL} approximately follows the linear

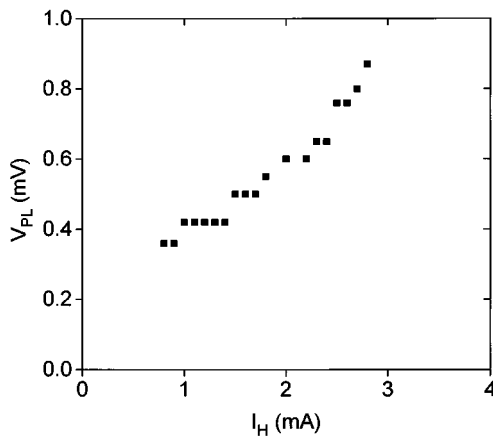


FIG. 5. Experimentally obtained dependence of the synchronization voltage $V_{\text{PL}}(I_H)$ on the tuning current I_H . In order to achieve synchronization, the field H has been adjusted at every point.

dependence on I_H that can be approximated by relation $V_{\text{PL}} = \gamma I_H$, where γ is a dimensional constant. According to Eq. (1), γ can be expressed as

$$\gamma = \bar{c}^* \frac{\Lambda_A k_B - \Lambda_B k_A}{\Lambda_B - \Lambda_A}. \quad (2)$$

For $\Lambda_A = \Lambda_B$ one meets the case of $I_H = 0$, i.e., no additional current is required to synchronize JJs.³ From Fig. 5 we estimate $\gamma \approx \gamma_1 = 0.3 \Omega$. The calculation based on measured $I_c(H)$ and layer thicknesses yields

$$\gamma \approx \gamma_2 \bar{c}^* = \frac{\Lambda_A \Lambda_B}{\Lambda_A - \Lambda_B} \left(\frac{dH_0^A}{dI_H} - \frac{dH_0^B}{dI_H} \right) \approx 0.5 \Omega.$$

One can see fair correspondence between two values γ_1 and γ_2 .

Measurements reported in this letter indicated only \bar{c}_- mode to be stable which corresponds to the out-of-phase synchronization of fluxon oscillations in two stacked junctions. The in-phase fluxon states are characterized by the velocity \bar{c}_+ and it has been reported stable in experiment for either very weak ($d_m < \lambda_L$)⁶ or rather strong ($d_m > \lambda_L$)¹¹ coupling cases. Although we did not observe the in-phase states, the suggested tuning technique should also be feasible for any thickness of the middle electrode, thus also for the parameter range of in-phase synchronization. In summary, stacked long Josephson junctions with rather large parameter spread have been investigated experimentally. It is shown, that it is possible to mutually synchronize the junctions in the stack by tuning a current through the middle electrode. We prove experimentally that such tuning can be carried out for relatively wide range of frequencies.

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