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**Dual flux-to-voltage response of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$
asymmetric parallel arrays of Josephson junctions**

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Abstract

We fabricated a parallel array of 440 $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ bicrystal grain boundary Josephson junctions having an inductive asymmetric loop configuration within the array. Families of current-voltage characteristics (*IVCs*) have been measured in the temperature range (4.7-92) K for various values of a magnetic flux applied via a control current I_{ctrl} . For both positive and negative current biases, I , current-driven chains of magnetic vortices are propagating along the array producing flux-flow current resonances on the *IVCs*. However, at 77 K and above, due to the system's inductive asymmetry the flux-flow is suppressed (enhanced) for negative (positive) I . Consequently, the system shows a dual flux-to-voltage response. For negative I it operates like a flux-interferometer having a rather sinusoidal $V(I_{ctrl})$ response. In contrast, for positive I the device's response $V(I_{ctrl})$ remains periodic but highly non-sinusoidal due to the interplay between multiple flux-flow modes. Below 60K such a dual behaviour is far less pronounced as a result of flux-flow modes being suppressed due to a decrease of the dissipation coefficient with temperature.

A parallel array of Josephson junctions (*PAJJs*) in an applied magnetic flux Φ can either exhibit flux-flow [1-5] or behave like a sensitive flux-to-voltage interferometer (magnetometer) [6]. When damping is low flux flow dominates *PAJJ*'s dynamics and they can be used as microwave generators [7-8] or superconducting transistors [9-10]. In both these cases the experimental signature of flux-flow is a series m of current resonances on the current-voltage characteristics (*IVCs*) whose voltage positions change periodically with the flux Φ . The flux periodicity is different for each current resonance m , and is given by a simple relation: Φ_0/m [3] (here Φ_0 is the flux quantum). Consequently *PAJJ*'s voltage response $V(\Phi)$ although periodic in Φ_0 is highly non-sinusoidal due to the interplay between multiple flux-flow current resonances, all having different flux periodicities. In contrast, when damping is high, flux-flow is weak and the current resonances have a reduced impact on the *IVCs*. As a result the *PAJJ* behaves like a flux-interferometer having a rather sinusoidal $V(\Phi)$ response [6]. All *PAJJs* investigated so far have been operated in either a flux-flow dominated regime or behaved as flux-interferometers. Here we report on a *PAJJ* device that simultaneously shows a flux-flow dominated highly non-sinusoidal $V(\Phi)$ response (for positive I) and a sinusoidal flux-interferometer-like $V(\Phi)$ response (for negative I). We induced such a dual behaviour by implementing an inductive asymmetric loop configuration within the array characterized by an enhanced flux-flow for positive I and a suppressed flux-flow for negative I . This dual flux-to-voltage behaviour is evident for temperatures in the range (77-89) K, while below 60K is far less pronounced due to a decrease in the dissipation coefficient with temperature resulting in the flux-flow modes being suppressed. Primarily we fabricated such asymmetric *APJJs* in order to enhance both the current amplification in superconducting transistors [11] and the power of microwave generation at 77K and above [12]. Indeed, the inductance asymmetry ensures the bias current produces a net inhomogeneous magnetic field along the array through self-field effects that lacks inversion

symmetry and results in a highly asymmetric $I_c(I_{ctrl})$ curve with high current gains [11]. On the other hand, the asymmetry, ensures that the reflected vortices at the edges of the *PAJJ* do not propagate backwards deep into the array to destructively interfere with the incoming train of vortices. This protects the flow of vortices in one direction (to the left in Fig.1) and the associated electromagnetic radiation amplification [12]. Here we complete these reported investigations by showing the voltage response of such *APJJs*.

Since the flux-flow current resonances are the main feature in the *IVCs* we measured a brief summary of the physics behind it will be given next. When a magnetic field, B , is applied perpendicular to a *dc* current-biased planar one-dimensional *PAJJ*, magnetic flux vortices will enter the array in the form of Josephson vortices. The bias current, I , flowing across the array produces a Lorentz force, F_L , which drives the Josephson vortices unidirectionally, forming a lattice of vortices moving with a speed, v . Theory shows that this is accompanied by an emission of small amplitude electromagnetic waves that propagate along the array [1]. When the vortex spacing is commensurate with the wavelength of emitted waves, resonant modes occur. This can be viewed as the phase-locking condition of the vortex velocity and the phase velocity of one of the self-induced modes. The experimental signature of such phase locking between a train of propagating vortices and their induced electromagnetic waves radiation in a *PAJJ* is a series of flux-flow current resonances on the *IVCs* [1, 2].

The *PAJJs* were fabricated by depositing high quality epitaxial, 100nm thick *c*-axis oriented $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (*YBCO*) films on $10 \times 10 \text{ mm}^2$, 24° symmetric [001] tilt, SrTiO_3 bicrystals by pulsed laser deposition [13]. A 200 nm thick Au layer was deposited in situ on top of the *YBCO* film to facilitate fabrication of high quality electrical contacts for electric transport measurements. The films with a critical temperature, T_c , of 92K were subsequently patterned by optical lithography and etched by an Ar ion beam to form a parallel array of 440

Josephson junctions (*JJ*). The array consists of 22 identical sets of 20 *JJ* each. All 440 *JJ* are 3 μm wide. The junctions are separated by superconducting loops of identical width (3 μm) but variable length. Thus, within each set of 20 *JJ* the length of the loops, and consequently, their inductance L_i , varies logarithmically from 13 μm to 8 μm . Consequently, the screening parameter $\beta_{Li} = 2\pi L_i I_{cJ} / \Phi_0$ is also changing monotonically within each set of 19 superconducting loops. Here I_{cJ} is the maximum Josephson critical current of each junction and L_i is the inductance of the superconducting loop between JJ_i and JJ_{i+1} , with $i=1, 2, \dots, 19$. An optical micrograph of a small part of such a *PAJJ* (containing 4 such sets of 20 *JJ* each) is shown in Fig. 1. We designed our *PAJJ* to have an average β_L of about 1.5 at 77K. We also implemented an asymmetric inductive loop configuration within the array by varying the value of β_L monotonically within each set of 20 *JJs* by about $\pm 15\%$ around its average. We chose a logarithmic dependence for β_L because it introduces a smaller degree of asymmetry than a linear dependence. This asymmetry enhances (supresses) the flux-flow for the case when the *PAJJ* is biased with a positive (negative) bias current. To understand this direction-dependent vortex-flow it is helpful to recall the mechanical analog of the system. The equations of motion of a *PAJJ* are identical of those of a chain of N identical pendulums, each of which is viscously damped and free to move transverse to the axis of the chain, driven by a constant torque, and coupled to its nearest neighbours by torsional springs K_i [2]. Since L_i varies monotonically along each set of 20 *JJ* so does the harmonic coupling K_i along each set of 20 pendulums. A vortex corresponds to a kink (soliton) propagating along the chain. Since it is easier for a kink to propagate in the direction of decreasing K_i than in the opposite direction it means the flux-flow is enhanced in the direction of decreasing inductance relative to the opposite direction. A similar asymmetric harmonic coupling K_i -induced ratchet potential that lacks inversion symmetry producing such a preferential directional motion for fluxons in *JJ* arrays has been previously investigated theoretically in

[14]. The bias current, I , is applied symmetrically via the central top and bottom electrodes. A magnetic field, B , is applied perpendicular to the planar array's structure via a control current I_{ctrl} . Consequently, an external magnetic flux Φ is coupled into the array. We have fabricated two such devices and both showed a similar behaviour.

Families of IVC 's were measured by a 4 point-contact method at various temperatures between 4.7K and 92K and for different values of the control current I_{ctrl} . Because the system is discrete, we expect both its voltage and current responses to be periodic in the applied flux Φ (proportional to I_{ctrl}) with period Φ_0 . The flux periodicity corresponds to one additional flux quantum Φ_0 in each loop. Since the loop area within each set of 20 JJ varies slightly by $\pm 15\%$ around its average value the flux periodicity should be understood in terms of a virtual average Φ_0 in each loop. The experimental observation of a flux periodicity in a system that lacks a precise geometrical periodicity but has a quasiperiodical structure emphasises the robustness of the interference effects. Such a robust flux periodicity has been previously observed in $PAJJs$ that were not designed on purpose to be aperiodical but were inherently slightly aperiodical due to the intrinsic variation of both junctions and loops parameters along the array. I_{ctrl} was varied in the range (-8mA, 8mA) in small steps of 15 μ A. This allows a scan over Φ that spreads over more than 8 periods at a given temperature with about 130 IVC 's per period. As a result, at all temperatures investigated (77-92) K the flux-flow resonances observed were much more pronounced for positive bias currents (the direction of I in Fig.1) than for negative ones. It was even possible for vortices to propagate in the low damping direction only. This is confirmed by the experiments at T=89K where flux-flow resonances are observed for positive bias currents only (see Fig. 2). For all temperatures measured the current step corresponding to the $m=1$ resonance had an amplitude about the same as the array's maximum critical current I_c . A family of 30 consecutive IVC 's measured at 89K are plotted in Fig. 2. From such families of IVC 's scanned over I_{ctrl} (or equivalently,

Φ), $I_c(I_{ctrl})$ for both positive and negative currents could be constructed (see Fig. 3). At temperatures this close to T_c the discreteness parameter β_{Li} is much smaller than 1. We performed numerical simulations based on a model developed earlier [6] in the limit of small β_L and from the modulation of I_c with I_{ctrl} we estimate an average value for β_L of 0.3 at 89K. Within this model, as for the case of two-junction interferometers, critical current modulation decreases monotonically with T while β_L increases monotonically with T. In the limit of $\beta_L \ll 1$, I_c versus Φ is expected to have a periodic pattern consisting of a series of maxima similar to a diffraction pattern of an optical multiple slit grating [6]. This behaviour is confirmed by the experiments at 89K: see the $I_c(I_{ctrl})$ dependence for negative bias currents and 3 different voltage criteria V_{cr} in Fig. 3 showing a symmetric and periodic pattern with a periodicity of about 2 mA. A single large flux-flow resonance is clearly visible for positive bias currents only (see Fig. 2). Its presence strongly affects the $I_c(I_{ctrl})$ dependence for positive values which now consists of a periodic two peak structure instead. The family of 30 *IVCs* shown on Fig.2 corresponds to an I_{ctrl} range covering precisely this periodic two peak structure. The current step resonance, corresponding to $m=1$, is tunable by varying Φ i.e., its voltage location strongly depends on Φ and, as expected, it has the same periodicity as $I_c(I_{ctrl})$. No such resonance is observed for negative bias currents (see the inset of Fig.2) due to the inductance asymmetry along the array, as explained earlier. At lower temperatures (77-84)K β_{Li} increases due to an increase in I_{cJ} and, as expected, multiple flux-flow resonances are observed corresponding to $m=1, 2, 3$ and 4. Again, due to inductance asymmetry along the array, these resonances are much more pronounced for positive current biases. The impact of *PAJJ*'s asymmetry on the families of *IVC*'s at 81K and 77K, shown in Figs. 4 and 5, respectively, is evident. Firstly, the flux modulation of both current and voltage are significantly stronger for negative current biases (see Figs. 4a and 5a). Secondly, the voltage response $V(I_{ctrl})$ (see Figs. 4b and 5b) can be approximated, to a better degree than the case of

positive current bias, as sinusoidal for all negative current biases, while it is highly non-sinusoidal for positive current biases. Then, for positive (negative) currents the extreme values in $V(I_{ctrl})$ are reached for different (approximately the same) values of I_{ctrl} as we change the current criteria I_{cr} from 0.4 mA to 1 mA (-1 mA to -0.4 mA) in Fig. 4b and from 0.5 mA to 1mA (-1 mA to -0.5 mA) in Fig. 5a. Also, the amplitude of voltage modulation is considerable larger for negative currents relative to the positive currents. It is important to note that the families of $V(I_{ctrl})$ recorded for different current biases I plotted in Figs. 3b, 4b and 5b, they all lack inversion symmetry with respect to 0. This is because the *PAJJ* is not magnetically screened and therefore the presence of the earth magnetic field breaks such symmetry. Since the perpendicular component to the *PAJJ* planar structure of the earth magnetic field B_{normal} is about 25 μ T it requires a significant shifting along the I_{ctrl} current axis in order to compensate for the earth magnetic field and therefore recover the inversion symmetry. Indeed, the magnetic field corresponding to $I_{ctrl}=1.8$ mA (the current period of $V(I_{ctrl})$ curves) is about 2.4 μ T which is much smaller than B_{normal} . The differences in the *IVCs* and $V(I_{ctrl})$ between the positive and the negative current biases are far less pronounced at temperatures below 60K. An example is shown in Fig. 6 for $T=57.5$ K. Similar characteristics have been measured at several other temperatures below 60K, namely, at 4.7K, 10K, and 30K. Indeed, the *IVCs* have a good degree of symmetry at these temperatures (see Fig.6a). Also, in this temperature range the $V(I_{ctrl})$ response becomes aperiodic (see Fig.6b) due to a significant suppression of the flux-flow modes due to a decrease in the dissipation coefficient $1/R_N$ (or damping) with temperature (here R_N is the normal resistance of the Josephson junction). A similar suppression of the flux-flow with decreasing T has been previously observed (both theoretically and experimentally) in *PAJJs* made of niobium low temperature superconductors [4, 5].

Conclusion

In conclusion, we have shown that an inductive asymmetric loop configuration within the array implemented in our *PAJJ* leads to a significant difference in the flux-flow for positive current biases relative to negative current biases and consequently to a corresponding different qualitative flux-to-voltage response. To achieve both an enhanced current amplification [11] and an enhanced microwave power generation [12] a *PAJJ* has to be operated in a regime of enhanced flux-flow, i.e., it should be biased with a positive current. The degree of asymmetry of our design can be further extended to enhance the contrast in the directional flux-flow and to improve *PAJJs* performances in these applications.

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Figure captions

Fig. 1. Optical micrograph of the *PAJJ* made of a parallel array of 22 identical sets of 20 *JJ*. Shown is a small central part of the array consisting of 4 sets of 20 *JJ*. Within each set all 20 *JJ* are 3 μ m wide and are connected via superconducting loops of identical width (3 μ m) and variable length (logarithmically decreasing from 18 μ m to 13 μ m).

Fig. 2. A family of 30 consecutive *IVCs* recorded at 89K for different values of I_{ctrl} . The horizontal arrow shows the $m=1$ flux-flow current resonance's direction of motion in the *IV* plane when increasing I_{ctrl} . The family is shown in 3 sets of 10 *IVC*'s each. For clarity *IVCs* 11 to 20 (21 to 30) have been shifted vertically by 0.1 mA (0.2 mA). The first (last) *IVC* within each set is shown in blue (red). The inset shows the same family of 30 *IVCs* for negative biases.

Fig. 3. (a) $I_c(I_{ctrl})$ and (b) $V(I_{ctrl})$ at 89 K for various voltage criteria V_{cr} and bias currents (criteria) I_{cr} , respectively. To obtain $I_c(I_{ctrl})$ and $V(I_{ctrl})$ one should draw straight lines parallel to the current axis at V_{cr} , and, respectively, parallel to the voltage axis at I_{cr} and consider the points where those lines cross the *IVCs*.

Fig. 4 (a) A family of 300 consecutive IVC s recorded at 81K for different values of I_{ctrl} in the range $(-2.25, 2.25)$ mA. I_{ctrl} is changed in steps of $15\text{ }\mu\text{A}$. (b) $V(I_{ctrl})$ for various bias currents I_{cr} in the ranges $(-1, -0.4)$ mA and $(0.4, 1)$ mA.

Fig. 5 (a) A family of 256 consecutive IVC s recorded at 77K for different values of I_{ctrl} in the range $(-2.325, 1.5)$ mA. I_{ctrl} is changed in steps of $15\text{ }\mu\text{A}$. (b) $V(I_{ctrl})$ for various bias currents I_{cr} in the ranges $(-1, -0.5)$ mA and $(0.5, 1)$ mA.

Fig. 6 (a) A family of 115 consecutive IVC s recorded at 57.5K for different values of I_{ctrl} in the range $(0, 4.56)$ mA. I_{ctrl} is changed in steps of $40\text{ }\mu\text{A}$. (b) $V(I_{ctrl})$ for various bias currents I_{cr} in the ranges $(-3, -1)$ mA and $(1, 3)$ mA.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6