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Phase-locked flux-flow Josephson oscillator

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We report on the observation of large rf induced steps due to phase-locking of unidirectional flux-flow motion in long quasi-one-dimensional Josephson junctions. The external microwave irradiation in the frequency range 62–77 GHz was applied from the edge of the junction at which the fluxons enter. The dependence of the amplitude of the phase-locked step on external magnetic field and microwave power has been measured. The observed zero-crossing steps have potential application in Josephson voltage standards. A simple model for the flux-flow as determined by the microwave driven boundary gate at the edge of the junction is presented.

In this communication we report on the first experiments on the phase locking of the *flux-flow oscillator* to an external millimeter-wave source. A long quasi-one-dimensional Josephson junction of the length L ($L > \lambda_J$, the Josephson penetration length) may be operated in the flux-flow mode, when a sufficiently high magnetic field is applied in the plane of the tunnel barrier. The fluxons are created at one boundary of the junction and annihilate at the other boundary. The autonomous flux-flow oscillator has been studied previously[1,2] showing promising results with respect to generated power and linewidth.

Phase locking of the *single fluxon oscillator*[3] has been studied experimentally[4–7] and theoretically,[8,9] often related to its potential application as local oscillator in superconducting millimeter-wave electronics.[10] The single fluxon oscillator is a long Josephson tunnel junction operated near zero external magnetic field with the fluxon(s) resonantly moving back and forth between reflections at the junction boundaries. Large rf induced steps[11,12] as well as self-induced steps[7,13] have been observed. As with short junctions, rf induced zero-crossing steps suggest application of series connected phase-locked long Josephson junctions for Josephson voltage standards.[14]

The samples were niobium-lead tunnel junctions on silicon substrates. The fabrication procedure has been described elsewhere.[15] The geometry is shown in Fig. 1. The junction area $L \times W = 480 \times 10\ \mu\mathrm{m}^2$ was defined by a window in the SiO layer, the thickness of which was 250 nm. In order to obtain a more homogeneous distribution of the dc current bias in the junction, the current I was fed through a set of equidistant fingers of the superconducting electrodes.[16] The external magnetic field was applied by a control current I_m in the Nb base electrode. Separate battery-powered dc current sources were used for I and I_m. All the dc lines were rf filtered at the top of the sample holder. A 9.4-mm-long finline antenna consisting of two exponential tapers[17] facilitated a close coupling of the junction to the E-band rectangular waveguide. The substrate with the sample was inserted into two parallel slots cut in the walls of the waveguide. The external rf power in the frequency range 62–77 GHz was applied from a frequency-locked Gunn oscillator with a linewidth of 120 kHz. The power P_a was measured at the input flange on the top of the waveguide by a calibrated powermeter. Magnetic shielding was achieved using a small cryogenic μ-metal can. The measurements were performed at 4.2 K.

Two samples studies showed very similar results. Here we present for simplicity the results for one of the junctions obtained at one particular frequency $f_{\mathrm{ext}} = 67.65$ GHz. The critical current of the junction at zero field was $I_c(0) = 6.2$ mA. The calculated value for λ_J was 36 μm. The frequency f_{ext} was chosen higher than the calculated plasma frequency $f_p = \omega_p/(2\pi) \approx 39$ GHz of the junction. f_{ext} has been chosen taking into account also the requirement to stay away from the standing wave resonance condition $L = m\lambda_{\mathrm{ext}}/2$, where m is integer and λ_{ext} is the wavelength corresponding to the external frequency f_{ext} in the junction. The calculated ratio L/λ_{ext} was 3.7.

The junction critical current I_c dependence on the control current I_m showed a well-known symmetrical behavior with a linear decrease of I_c for small I_m. The critical magnetic field of this junction obtained from the extrapolation of the symmetrical linear slopes $I_c(I_m)$ to $I_c = 0$ corresponded to $I_m^c \approx \pm 1.75$ mA. The dc I-V characteristics for $I_m > I_m^c$ displayed the well-known behavior with the flux-flow step at voltage V_{ff} being approximately proportional to I_m. For a not very high I_m (corresponding to the average number of fluxons in the junction n being less than $n_{\max} \approx L/\lambda_J$), the lower voltage part of the main flux-flow step was split into several Fiske-type steps due to the reflections of the fluxons from the edges of the junction. The voltage of the first rf induced step $V_1 = \Phi_0 f_{\mathrm{ext}} = 139.9\ \mu$V (here Φ_0 is the magnetic flux quantum) corresponded to about $n = 4$ fluxons moving in the junction.

Because of the sample geometry, the rf signal was applied asymmetrically to the ends of the junction. In the presence of microwaves for the fixed polarity of the control current I_m, this is manifested as a difference in the shape of the I-V curves at different polarities of the bias current I.

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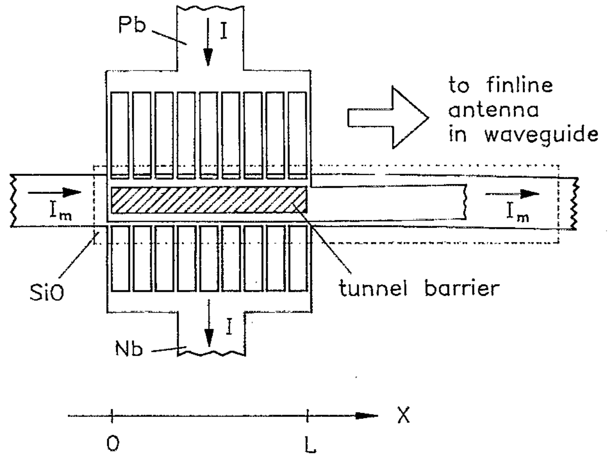

FIG. 1. Sample geometry (vertical scale has been changed for clarity).

For the orientation shown in Fig. 1 with $I_m > 0$, at $I > 0$ the fluxons enter the junction from its right edge $X = L$ and move in the direction opposite to the finline antenna, while at $I_m < 0$ they enter the junction from its left edge $X = 0$ and move towards the antenna. The asymmetry of the microwave coupling to the junction has also been checked by measuring the $I_c(I_m)$ pattern at small rf power. For $I_m > 0$ the application of an rf signal dominantly influenced I_c^+ (I_c value for $I > 0$) and produced almost no change in I_c^- (for $I < 0$). An applied signal of $P_a = 3\ \mu$W produced a shift $\Delta I_c^+ \approx 2.4$ mA of $I_c^+(I_m)$ linear slope, while a change of I_c^- of less than 0.1 mA was observed.

Figure 2 shows a typical example of an *I-V* curve without (a), and with (b), microwaves applied. The flux-flow voltage V_{ff} has been chosen to be close to the first rf induced step at $V = V_1$. The asymmetry of an unperturbed *I-V* curve seen for the curve (a) in Fig. 2 has only been observed for I_b corresponding to the voltage V_{ff} in the range 80–250 μV. At higher I_b the flux-flow step was perfectly symmetrical. We suppose that this is due to the strongly asymmetric (with respect to the boundary conditions) coupling of the junction. Application of the microwaves causes a very pronounced locking of the junction indicated by large constant voltage step for $I > 0$. The current range of the step is about 50% of the critical current $I_c(0)$. Locking has also been observed for the opposite direction of the bias current I at $V = V_{-1} < 0$. However, the locking occurred in a much narrower current range and at a sufficiently higher rf power.

By taking into account the asymmetric coupling the microwaves into the junction, the locking of the flux-flow in the junction to the rf induced step can be explained qualitatively as follows. The locking is the strongest if the fluxons move from the right to the left as shown in Fig. 1 ($I_m > 0, I > 0$). The instantaneous value of the local magnetic field H_L at $X = L$, which determines the energy threshold for the fluxons entering the junction, is modulated by the magnetic component of microwave field applied. Once, during a period $1/f_{\text{ext}}$ of the external signal, the value of H_L reaches its maximum and lets a fluxon enter the junction. It means, that *microwaves serve as a boundary gate which synchronizes the sequence of fluxons entering the junction.* During the phase-locking regime, one fluxon enters the junction per one rf period and the dc voltage of the junction is locked to $V = V_1$. On the other side, for the opposite direction of the bias current, the fluxons enter from the left side at $X = 0$ and move in the opposite direction. Because $f_{\text{ext}} > f_p$, the waves at the external frequency can propagate along the junction and with some attenuation reach the left edge $X = 0$ of the junction. This suggests that the locking (but less strong) should be observed also for the opposite direction of the bias current, as observed in Fig. 2. Of course, we cannot exclude also a certain microwave power coupled from the stripline into the junction from the left side, but it is expected to be smaller due to an open-end type boundary condition in the stripline.

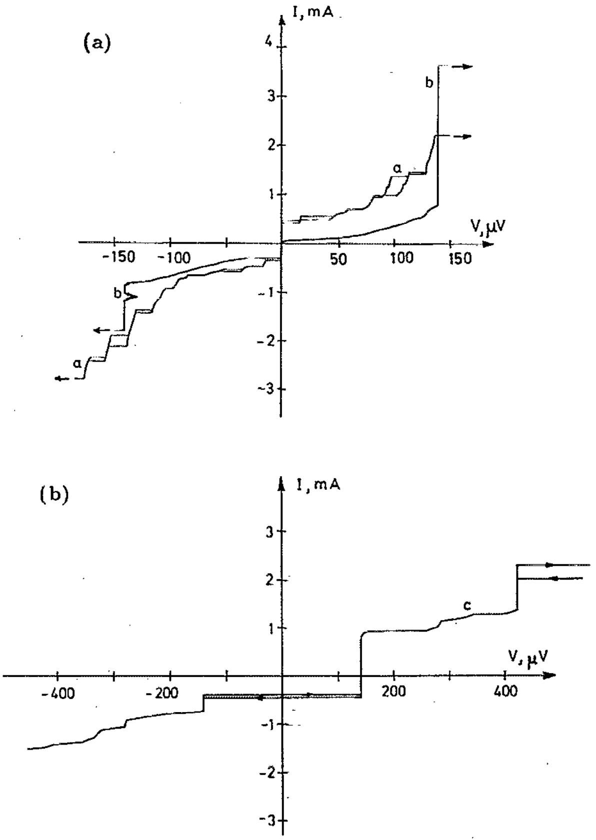

FIG. 2. Typical *I-V* curves without (a), and with (b) and (c), applied microwaves at $f_{\text{ext}} = 67.7$ GHz. In cases (a) and (b) the power level was $P_a = 17\ \mu$W, control current $I_m = 1.80$ mA. Zero-crossing step (c) was obtained for $P_a = 135\ \mu$W, $I_m = 1.25$ mA. $T = 4.2$ K.

The results on tuning of the phase-locked steps by magnetic field (proportional to the control current I_m) are shown in Fig. 3(a). The dependence on I_m has been measured for a very low rf power $P_a = 3.0\ \mu$W. In Fig. 3(a) the locking range for the first step $V = V_{+1}$ is indicated by open squares. The largest locking range is observed for this step in the resonant case when $V_{ff} \approx V_{+1}$. With increasing I_m the voltage V_{ff} also increases and reaches the level of the second step $V = V_{+2}$, where the locking is also ob-

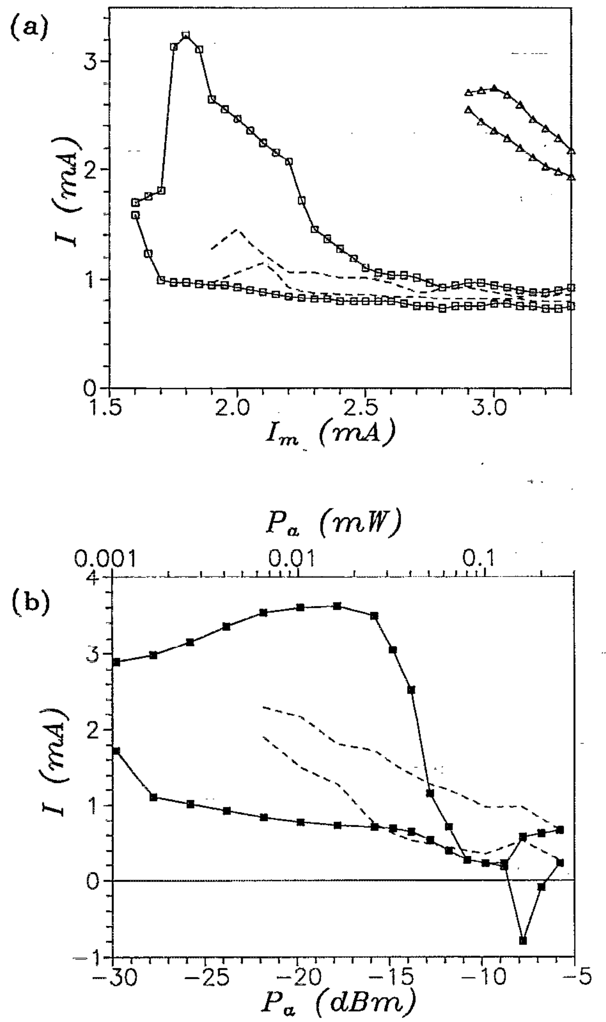

FIG. 3. Bias current I tuning ranges for the phase-locked steps. (a) Magnetic field (control current I_m) dependence at $P_a = 3.0\,\mu$W: first step $V = V_{+1}$ for $I>0$ (open squares), second step $V = V_{+2}$ for $I>0$ (open triangles), first step $V = V_{-1}$ for $I<0$ (dashed lines). (b) Power dependence at $I_m = 1.80$ mA: first step $V = V_{+1}$ for $I>0$ (solid squares), first step $V = V_{-1}$ for $I<0$ (dashed lines).

served [the area inside the open triangles in Fig. 3(a)]. In this case, in one period of rf field, two fluxons enter the junction from $X=L$. The locking range at $V = V_{-1}$, measured for the opposite polarity of the bias current, was very small as shown by dashed lines in Fig. 3(a).

The tuning of the phase-locked steps by rf power at fixed control current $I_m = 1.80$ mA (close to the resonant case $V_{ff} \approx V_1$) is shown in Fig. 3(b). The phase-locked state at the step $V = V_{+1}$ was stable over almost two decades of rf power. At larger power the current range of locking step decreased and a zero-crossing step at $V = V_{+1}$ was observed. At all powers the locking range at $V = V_{-1}$ (shown by dashed lines in Fig. 3(b) was noticeably smaller than that at $V = V_{+1}$.

Large zero-crossing steps at $V = V_{+1}$ have been also observed for a power P_a about 100–150 μW outside the autonomous flux-flow region at small I_m between 0.8 and 1.4 mA. These conditions correspond to quite low external magnetic field but rather large rf power. In this case even at zero bias current the fluxons can be generated by asymmetrically coupled rf field on one side of the junction and pushed one by one along the junction yielding a dc voltage at $I=0$. Naturally, the fluxon frequency is locked to the external rf pump and the voltage is equal to V_1.

There is an important difference between our flux-flow-type zero-crossing steps and the conventional zero-crossing steps in both short,[14] and long,[11,12] Josephson junctions. In our case, in a certain current range (about 1 mA) around $I=0$, *the only stable step* in the whole *I-V* curve is the one at $V = V_1$. It means that it may be used as a voltage standard without a parallel resistive load to generate a load line for biasing the junction. The quantized dc voltage can be obtained in a flux-flow oscillator at $I=0$ by simply switching on the rf power and the magnetic field. The reversal of the magnetic field also reverses the voltage which is convenient in order to correct for thermal voltages.

In summary, we have studied the phase locking of the Josephson flux-flow oscillator to an external rf source in the frequency range 62–77 GHz. We have observed large rf induced steps for the case when the external source is coupled mainly to the boundary at which the fluxons enter the junction. The external source operates like a gate at the boundary which synchronizes the fluxons entering the junction. Resonant dependence of the phase-locked step amplitude on external magnetic field has been observed. The large zero-crossing steps found suggest the use as series array Josephson voltage standard.

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