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# Millimeter-wave-induced fluxon pair creation in flux-flow Josephson oscillators

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We observe a new type of dynamical state in long Josephson junctions. Millimeter-wave irradiation in the frequency range $f_{\rm ext}$=62–77 GHz was applied to a long junction biased in the flux-flow mode. Besides an ordinary flux-flow step satellite, flux-flow steps with voltage spacing corresponding to $2f_{\rm ext}$ were observed. The dependence of the amplitude of the satellite steps on external magnetic field and microwave power was measured. An explanation of the satellite steps as mixing products due to the microwave-assisted reflection of fluxons into antifluxons at the junction boundary is presented.

The dynamics of fluxons in quasi-one-dimensional long Josephson junctions has received increasing interest over the last decade as a model system for soliton physics and also because of possible applications for microwave generation.[1] When subjected to a sufficiently high external magnetic field, a long Josephson junction operates in the undirectional flux-flow mode. The fluxons are created at one boundary of the junction and annihilate at the other boundary. The autonomous flux-flow dynamics has been studied in detail so far[2–6] showing promising performance characteristics such as large generated power and narrow linewidth.

In the present paper we study the flux-flow dynamics in the presence of external millimeter-wave irradiation. In the $I$-$V$ characteristics we observe a new type of resonant flux-flow satellite steps, which can be interpreted as parametric mixing of the flux-flow oscillations with the external high-frequency signal. We suggest a natural qualitative explanation for these new steps as being due to the microwave-assisted reflections of fluxons into antifluxons at the junction boundary.

The samples used in the measurements were Nb-Pb tunnel junctions made on silicon substrates. The fabrication procedure has been described elsewhere.[7] The junction area $L \times W = 480 \times 10$ $\mu$m$^2$ was determined by a window in the SiO layer, the thickness of which was 250 nm. In order to achieve a more homogeneous dc current distribution in the junction the bias current $I$ was fed through a set of equidistant fingers of the electrodes. The external magnetic field was applied by a control current $I_m$ flowing in the Nb base electrode. Both currents were supplied from separate battery-powered current sources. The layout of the substrate is shown in Fig. 1. The coupling of the junction to the $E$-band waveguide was made by a long finline antenna consisting of two exponential tapers.[8] The external rf power in the frequency range 62–77 GHz was applied from a frequency-locked Gunn oscillator. The power $P_a$ was measured at the input flange at the top of the waveguide by a calibrated power meter. Magnetic shielding was achieved using a small cryogenic $\mu$-metal can. The measurements were performed at 4.2 K.

We present here the results obtained for two samples $A$ and $B$. The critical currents of the junctions $I_c(0)$ at zero field were 6.2 and 7.7 mA, respectively. The calculated values for Josephson penetration depth $\lambda_J$ was about 30 $\mu$m. The external frequency $f_{\rm ext}$ was higher than the calculated plasma frequency $f_p = \omega_p/2\pi \approx 40$ GHz in the junctions.

The dependence of the critical current $I_c$ on the control current $I_m$ showed the well-known symmetrical behavior with a linear decrease of $I_c$ for small $I_m$. The critical magnetic field of this junction obtained from an extrapolation of the symmetrical linear slopes $I_c(I_m)$ to $I_c = 0$ corresponded to $I_m = I_p \approx \pm 2$ mA. The $I$-$V$ curves for $I_m > I_p$ displayed the well-known flux-flow behavior with the flux-flow step at the voltage $V_{ff}$ approximately proportional to $I_m$.

The sample geometry is chosen to feed the rf signal asymmetrically into the junction. In the presence of microwaves for fixed polarity of the control current $I_m$, this was observed as a difference in the shape of the $I$-$V$ curves at different polarities of the bias current $I$. The asymmetry of the microwave coupling into the junction may also be inferred from measurements of the $I_c(I_m)$ dependence for small applied rf powers. For $I_m > 0$ the presence of the rf signal strongly influenced $I_c^+$ ($I_c$ value for $I > 0$) while it has no influence on $I_c^-$ (for $I < 0$).

Figure 2 shows a typical example of the $I$-$V$ curve for $I > 0$ at $I_m = -5.3$ mA without (curve $a$) and with ($b$)

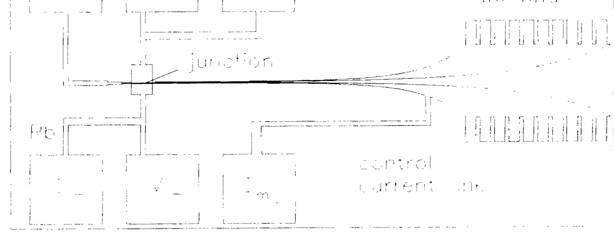


FIG. 1. Sample layout. The substrate size is $12.5 \times 6.2$ mm$^2$.

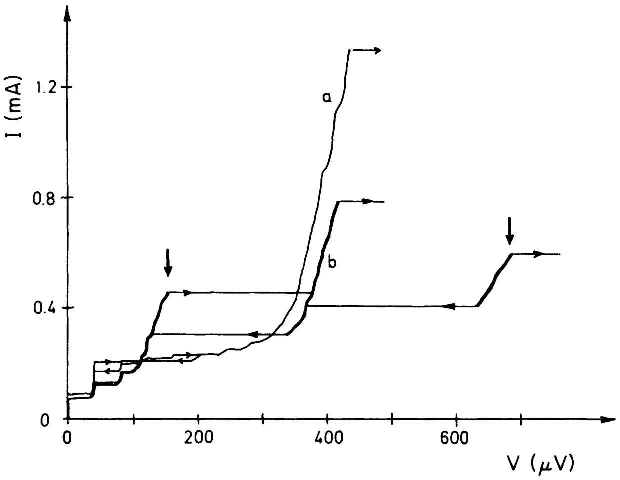


FIG. 2. Typical $I$-$V$ curves for the junction $B$ at $I>0$ (curve $a$) without and ($b$) with applied microwaves at $f_{ext}=68.0$ GHz. Power level, $P_a=100$ $\mu$W; control current, $I_m=-5.3$ mA; temperature, $T=4.2$ K. Satellite steps at voltages $V_{-1}\approx 140$ $\mu$V and $V_{+1}\approx 680$ $\mu$V are seen in curve $b$. The arrows indicate the satellite steps discussed in the text.

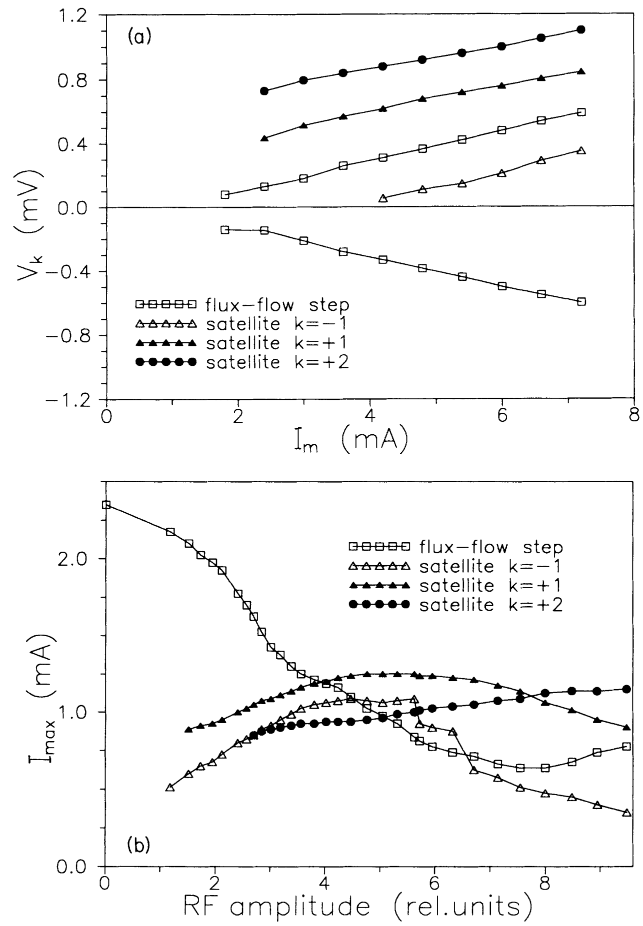


FIG. 3. (a) The dependence of the asymptotic voltage of the various steps on magnetic field (control current $I_m$) at $P_a=3.0$ $\mu$W and $f_{ext}=70.2$ GHz for junction $A$. (b) Power dependence of the amplitude of the steps for junction $A$ at $I_m=-5.4$ mA, $f_{ext}=75.4$ GHz, and $I>0$; $T=4.2$ K.

microwaves, applied at the frequency $f_{ext}=68.0$ GHz. Without microwaves the $I$-$V$ curve displays at $V=V_{ff}\approx 400$ $\mu$V a pronounced flux-flow step. Under the influence of microwave irradiation its current amplitude is suppressed and additional *satellite steps* appear on both sides of the flux-flow step at voltages $V_{-1}\approx 140$ $\mu$V and $V_{+1}\approx 680$ $\mu$V. The differential resistance of these new steps and their general shape resembles that of the flux-flow step. The voltage spacing between the flux-flow step and its satellites is close to $\Delta V=2\Phi_0 f_{ext}\approx 280$ $\mu$V, which corresponds to the voltage of the *second* ordinary rf-induced (Shaprio) step at this frequency. Or, in other words, we observe the mixing products of the flux-flow oscillations only with the *second* harmonic of external frequency. We observed the similar picture also for negative bias current ($I<0$, where the fluxons move in the opposite direction), but the suppression of the flux-flow step by microwaves was considerably weaker and the satellite steps were smaller in amplitude and much less stable. We believe that this confirms the asymmetry (with respect to the boundary conditions) of the microwave coupling to the junction.

The dependence of the aysmptotic voltage of the flux-flow and satellite steps on the magnetic field (proportional to the control current $I_m$) is shown in Fig. 3(a). The measurements were performed with the junction $B$ at $P_a=3.0$ $\mu$W and $f_{ext}=70.2$ GHz. All the tuning curves show similar approximately linear increasing of the voltage with magnetic field. The voltage spacing between steps remains approximately constant about $\Delta V\approx 250$–$300$ $\mu$V. A certain variation of $\Delta V$ with changing $I_m$ is mainly due to the disturbance of the shape of the flux-flow step and its satellites at the voltages corresponding to the conventional rf-induced (Shapiro) and Fiske-type resonances[9] in the junction.

The data in Fig. 3(a) show the main difference between the new rf-induced steps (satellite steps) and the ordinary Shapiro steps: *The asymptotic voltages of the satellite steps increase with magnetic field in the same way as that one of the flux-flow step, while the voltage spacing between steps remains constant and approximately equal to* $\Delta V=2\Phi_0 f_{ext}$. The ordinary Shapiro steps were always observed as vertical steps at the voltages $V_n=n\Phi_0 f_{ext}$. The Shapiro steps, however, showed a much smaller current amplitude than the flux-flow and the satellite steps. Only at large applied powers were they of appreciable size. The only exception was in the vicinity of $V_{ff}\approx V_n$ where phase locking of the flux-flow oscillations to the external frequency has been observed.[10]

The dependence of the current amplitude of the steps on the applied microwave power at fixed control current $I_m=-5.4$ mA has also been measured. The results for the junction $A$ are shown in Fig. 3(b). The amplitude of the main flux-flow step decreases steadily with power. The amplitude of the satellite steps first increase at small power and then decrease at larger powers. At powers larger than the upper limit shown in Fig. 3(b) the steps become very much mixed with the Shapiro steps. Since the latter also oscillate with rf power it is difficult to distinguish between the different types of steps. In the low power region the power dependence of the step amplitude resembles the classical Shapiro-step amplitude dependence on power and step number. The steps at $V_{-1}$ and $V_{+1}$ display the maximum amplitude at approximately the same power. The abrupt changes in the amplitude of the step at $V_{-1}$ is probably due to the competition between this step and the nearby first Shapiro step.

By taking into account the asymmetric coupling of the microwaves into the junction, a qualitative mechanism for the excitation of a satellite step in the flux-flow regime can be suggested as follows. The steps are largest and most stable if the fluxons move from the left to the right as shown in Fig. 4 ($I_m < 0, I > 0$). In the usual flux-flow regime they annihilate at the junction boundary $x = L$ closest to the microwave source. The instantaneous value of the local magnetic field $H_L$ at this point, which determines the energy obtained by fluxons colliding the junction boundary, is modulated by the magnetic field of the applied microwave power. Let us consider that once during a time period $1/f_{ext}$ of the external signal the value of $H_L$ reaches its maximum thus causing a fluxon to being reflected into an antifluxon moving back into the junction (process indicated as *a* in Fig. 4). It means, that *the microwaves produce one antifluxon per each period* $1/f_{ext}$. For a reflected antifluxon there are two possibilities: to annihilate with the next fluxon arriving at the boundary (process *b*) or to propagate all the way through the junction to its other boundary (process *c*). The first process is more likely to take place at lower bias current where the energy of the fluxon is relatively small. In this case *b* the measured average dc voltage is the same as for the usual flux flow. Instead of two $2\pi$ phase shifts at $x = L$ (corresponding to two sequential fluxons leaving the junction) we get one $4\pi$ phase shift (corresponding to the reflection of a fluxon into an antifluxon and its annihilation with the next incoming fluxon) and the average dc voltage remains unchanged. Another process *c* happens at higher bias current when the energy of the fluxons is large enough to permit the fluxon and antifluxon to pass through each other. The reflected antifluxon under the influence of the bias current travels back and reflects again into a fluxon. The net result is that two additional flux quanta contribute to the dc voltage per each $1/f_{ext}$ time period. This means that the dc voltage corresponding to the regime *c* will be higher than the flux-flow step by an amount $\Delta V = 2\Phi_0 f_{ext}$ thus obtaining the satellite step at $V = V_{+1}$. The reflection of two fluxons into two antifluxons per each period $1/f_{ext}$ requires higher microwave power and gives the satellite step at $V = V_{+2}$, and so on. Probably, a similar microwave phase depending process can explain also the satellite as $V = V_{-1}$, but this should be justified by numerical simulations.

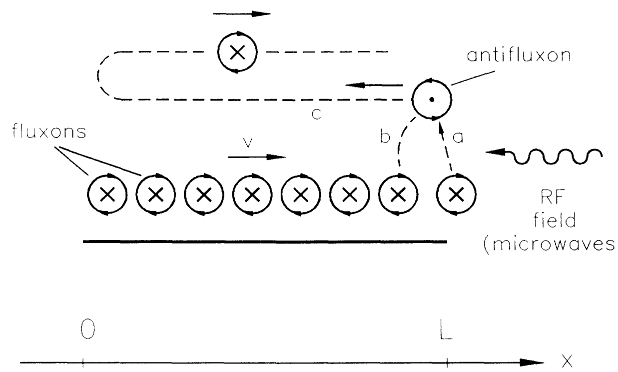


FIG. 4. A schematic representation of the dynamical processes in the junction induced by microwaves, corresponding to the satalite flux-flow steps appearing in $I$-$V$ characteristics (for details see the text).

For negative bias current the fluxons move in the opposite direction. Because $f_{ext} > f_p$, the waves at the external frequency can propagate along the junction and with some attenuation reach the opposite edge of the junction. This suggests that similar steps of smaller size should be also observed for the opposite direction of the bias current $I$ or control current $I_m$, as was confirmed in the experiment. Of course, we cannot exclude the possibility that a certain microwave power is coupled from the stripline into the junction from the left side. However, this is expected to be smaller due to the open-end-type boundary condition in the stripline.

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