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FREQUENCY CONVERSION WITH SUPERCONDUCTING POINT CONTACTS OPERATING AS OSCILLATOR-MIXERS AND ITS APPLICATION TO THE MEASUREMENT OF THE LINEWIDTH OF THE JOSEPHSON CURRENT AT VERY HIGH FREQUENCY

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Résumé. — Le phénomène de conversion de fréquence Josephson est étudié dans la gamme des ondes millimétriques et submillimétriques à l'aide de contacts à pointe supraconducteurs Nb-Nb à 4,2 K fonctionnant en oscillateur-mélangeur, avec une fréquence intermédiaire de 0,1 ou 9,2 GHz. L'observation directe de la fréquence de conversion est réalisée à 9,2 GHz grâce à un récepteur superhétérodyne, dans la gamme de fréquence Josephson 145-1 600 GHz. Par contre, les expériences réalisées avec une fréquence intermédiaire f_i de 0,1 GHz montrent que pour cette faible valeur de f_i les signaux observés ne sont pas reliés directement au phénomène de conversion de fréquence mais à des effets dus au bruit. Nous proposons une analyse du mécanisme de conversion de fréquence dans une jonction Josephson fonctionnant en oscillateur-mélangeur, qui tient compte du bruit et des effets de réaction induits dans la jonction polarisée en courant.

Nous avons ensuite recherché le rôle du bruit dans des contacts à pointe supraconducteurs utilisés comme oscillateur-mélangeur jusqu'à des fréquences de l'ordre de 450 GHz, le courant Josephson étant mélangé avec des harmoniques d'un signal extérieur. Le signal émis à la fréquence intermédiaire est détecté à 9,2 GHz et sa largeur de raie mesurée. Puisqu'aux très hautes fréquences, le courant continu de quasiparticules est prépondérant dans un contact Josephson, nous avons comparé les résultats théoriques de Scalapino avec nos résultats expérimentaux.

Abstract. — The Josephson frequency conversion in the millimeter and submillimeter wave region is studied with superconducting Nb-Nb point contact junctions at 4.2 K, using the contact both as the local oscillator and the mixer with intermediate frequencies of 0.1 and 9.2 GHz. Frequency conversion signals are only detected in the latter case with a microwave receiver at 9.2 GHz in a range of Josephson frequencies between 145 and 1 600 GHz. The experiments with intermediate frequency f_i of 0.1 GHz indicate for this small value of f_i that the observed signals are not related to frequency conversion but noise effects. An analysis of the frequency conversion mechanism in a Josephson junction operated as an oscillator-mixer is proposed which includes the noise effects and also the feedback effects induced in a junction driven by a constant current source.

We have then investigated the noise properties up to 450 GHz of superconducting point-contacts using the junction as an oscillator-mixer where the Josephson current is mixed with harmonics of an externally applied signal. The emitted intermediate frequency is detected at 9.2 GHz and its linewidth is measured. In the very high frequency range the dc quasiparticle current dominates in a Josephson weak-link and we compare the corresponding theoretical linewidth calculated by Scalapino with our experimental results.

We have studied the Josephson frequency conversion in superconducting contacts operating as oscillator-mixer in the purpose of using this method to measure the fluctuations of the Josephson current at very high frequencies (several hundred gigahertz), a frequency domain where sensitive narrow band receivers are not yet easily realized. Consequently, in our experimental set up, the point-contacts are in an X-band wave guide and have no shunt parallel resistance as in the Resistive-Squid. Then these driven-current contacts are not perturbed as in a resonant cavity and all their dc parameters are measured in each experiment. The applied external signal is generally at 145 GHz but in some experiments is at 32 GHz.

Two if detection systems were used at 0.1 and 9.2 GHz. We describe first what are the observed signals in both cases when the contact is made to oscillate at $\omega_0 = 2 eV_0/h$ (V_0 = measured dc voltage) and an external signal at $\omega_e/2\pi = 145$ GHz is applied.

1. Experimental results. — **1.1 LOW INTERMEDIATE FREQUENCY.** — Figure 1 represents the I - V characteristic with the rf induced steps and the 100 MHz signal simultaneously detected. It shows that the voltage difference between a step and a neighbouring maximum signal strongly varies and is always much larger than the $\sim \pm 0.2$ μ V voltage difference expected with 100 MHz if. Also there is

FIG. 1. — 100 MHz response versus voltage of a Nb-Nb contact at 4.2 K operated as a Josephson oscillator mixer irradiated at 145 GHz with the corresponding V - I characteristic recorded simultaneously. The time constant is 1 s. The broad maxima detected on either side of each step occur at voltages such that the voltage difference with the neighbouring step is between ~ 6 and $20 \mu\text{V}$, and result from low frequency noise current components.

a signal near the zero step where no mixing signal is expected. Figure 2 is an expansion of the 100 MHz signal near the 3rd step recorded versus dc current I , in order to better observe the details near the step. It shows that the signal is correlated with the dynamic resistance R_D ($R_D = \Delta V_0 / \Delta I$). More precisely, the signal is always found to be proportional to R_D^α with $0 < \alpha \lesssim 2$. Here on figure 2 a good fit is obtained between the signal and the theoretical curve $S \sim R_D^2$ (black dots). These results and others to be published later [1] show without doubt that the 100 MHz detected signals are not the expected mixing signals between ω_0 and ω_e and must be attributed to some noise effects. We shall come back later on their nature.

1.2 HIGH INTERMEDIATE FREQUENCY. — Figure 3 shows typical results with 9.2 GHz if corresponding to mixing between ω_0 and the third harmonic of ω_e . The I - V characteristic and the if signal are simultaneously detected during the same run. With this large if the Josephson frequencies corresponding to both maximum obey very well to the frequency conversion condition, that is here $900 \pm 19 \mu\text{V}$. Figure 4 shows on the left part an enlarged view of the 9.2 GHz signal near the voltage $900 - 19 \mu\text{V}$. The two peaks separated by 60 MHz correspond to the frequency of the superheterodyne local oscillator $\pm 30 \text{ MHz}$. These peaks which were not resolved on figure 3 because of the sweep rate are now clearly seen and give a good idea of the resolution obtained

FIG. 2. — Expanded recording of the 100 MHz signal around the 3rd step of figure 1, plotted versus the current bias of the point contact. The time constant is 3 s, and the VIC is also simultaneously recorded. To show how the 100 MHz is strongly correlated to the dynamic resistance R_D , the black dots represent the variation of R_D^2 fitted at the maxima of the 100 MHz signal response.

FIG. 3. — Frequency-converted signal at 9.2 GHz obtained near the 3rd step of a Nb-Nb contact at 4.2 K operated as a Josephson oscillator-mixer irradiated at 145 GHz with the VIC simultaneously recorded. The time constant is 0.3 s.

in the method. The frequency conversion phenomenon shown with the 3rd harmonic of $\omega_e / 2\pi = 145 \text{ GHz}$ has been observed for all harmonics comprised between $n = 1$ and $n = 11$, that is up to 3.3 mV corresponding to a Josephson frequency $\sim 1600 \text{ GHz}$. The right part of figure 4 shows a result obtained for the 10th harmonic ($\omega_0 / 2\pi \sim 1450 \text{ GHz}$).

To sum up these experimental results, we obtain frequency conversion signals with large if, but not with small if.

FIG. 4a. — Expanded recording of 9.2 GHz frequency converted signal of figure 3 relative to the contact voltage 900 — 19 μ V. The two separated peaks (not resolved in Fig. 3) correspond to the frequencies $\omega_{LO}/2\pi \pm 30$ MHz where ω_{LO} is the local oscillator frequency of the superheterodyne receiver.

FIG. 4b. — Frequency-converted signal at 9.2 GHz obtained near the 10th step ($V_0 \approx 3$ mV, $\omega_0/2\pi \approx 1450$ GHz) of a Nb-Nb contact at 4.2 K irradiated at 145 GHz. The time constant is 3 s.

2. Interpretation of the different nature of the experimental results with high and low if. — To explain the differences of the observed signals in the experiments with low and high if we find necessary to take into account not only the fluctuation phenomena linked with the current flow in the junction, but also the feedback effects generated by the contact parallel impedance, whose effects are considered in a phenomenological way. Consequently we write $V(t)$ the time dependent voltage across the driven current contact as follows :

$$V(t) = V_0 + V_1(t, \omega_e) + V_2(t, \omega_0) + V_3(t, \omega_i) + V_n(t)$$

where V_0 is the mean dc voltage, $V_1(t, \omega_e)$ the ac voltage due to irradiation by the external signal at frequency ω_e and we assume that they are the main terms. Feedback generated by the contact parallel impedance is only taken into account by the components $V_2(t, \omega_0)$ and $V_3(t, \omega_i)$. Noise is included with $V_n(t)$. Introducing $V(t)$ in the expression of the Josephson current and applying the FM noise theory developed by Stewart [2] the calculations give the following result [1] : beside mixing current components at the frequencies $\omega_i = |\omega_0 \pm n\omega_e|$, low frequency noise components appear in the development in Bessel-Fourier series of the Josephson current. The ratio N of the detected power corresponding to the low frequency fluctuation current components to the detected power corresponding to the frequency conversion signal at ω_i is in first order proportional to $\Delta\omega_0^2/(\Delta\omega_0/2)^2 + \omega_D^2$ where $\Delta\omega_0$ is the Josephson linewidth and ω_D the detection frequency. Then with high if (e. g. 9.2 GHz) where it is easy to obtain $\omega_D = \omega_i \gg \Delta\omega_0$, N is very small and proportional

to $(\Delta\omega_0/\omega_D)^2$. Frequency conversion with a Josephson oscillator-mixer may be observed under these conditions. But when $\omega_D \sim \Delta\omega_0$ (e. g. with if ~ 100 MHz) N is of order of unity and the mixing current components are buried in noise current components. This interpretation allows to explain fairly well all the characteristics of the observed 100 MHz signals and confirms that they are not mixing signals but are related to the detection of noise current components.

The presented theoretical interpretation confirms the fact that up to now we believe that the only cases where frequency conversion at high frequencies with a Josephson oscillator mixer has been demonstrated without any ambiguity are experiments using high if (~ 9 GHz) that is the experiments of Longacre [3], [4] and ours. In these experiments, the noise effects come out by a lowering of the detected level and a broadening of the signal linewidth. Our analysis points out that it is difficult to observe the true frequency conversion signal with current polarized contacts whose I - V characteristic often present large R_D in the vicinity of the steps and in this situation the condition $\Delta\omega_0 \ll \omega_D = \omega_i$ is not easily realized. Consequently it seems to us that the use of low if for a high frequency Josephson oscillator-mixer, even with a Resistive-Squid to reduce the fluctuations, may not give necessarily frequency conversion signals. In the latter case, as the dc voltage to be applied is rather large and the currents necessary to draw the shunt are very high (larger than 1 A) [5], bias current fluctuations may also be of importance. Then, one must make experimentally sure that the Josephson linewidth of the device is much smaller than the if, and that signals are seen at both Josephson frequen-

FIG. 5. — Experimental reduced Josephson oscillation linewidth of superconducting point contacts as a function of dc voltage compared to the theoretical calculation by Scalapino and Stephen. The white circle is obtained by direct observation of the emission at the fundamental Josephson frequency (9.2 GHz). The other points correspond to linewidth measurements of the intermediate frequency radiated at 9.2 GHz by point-contacts exposed to external radiations at 32 and 145 GHz.

cies $\omega_0 = \omega_e \pm n\omega_i$ to have a guarantee that the if observed signals are frequency conversion ones.

3. Fluctuation of the Josephson current at very high frequencies. — In figure 5 the solid lines show as a function of the dc voltage (or Josephson frequency) the theoretical reduced oscillation linewidth for a Josephson junction as determined by Scalapino [9] and Stephen [10]. The two lines on the right part correspond to the two limits $I = I_q$ (quasiparticle current) and $I = I_p$ (pair current) [6]. As the I - V characteristic indicates that at high voltage the pair current is much smaller than the quasiparticle current, one expects experimental results to fit the lower line. The different experimental points correspond to Josephson linewidth at frequencies 32 ± 9.2 GHz

(square dots), 145 ± 9.2 GHz (black triangular dot), $3 \times 145 \pm 9.2$ GHz (white triangular dot) measured with point-contacts operated as oscillator-mixers with high if (9.2 GHz) and at 9.2 GHz owing to direct emission from point-contacts [7]. For all the measurements corresponding to the use of the oscillator-mixer method the points are above the theoretical curve by a systematic factor of 1.5 to 2 in the best conditions, that is when the measurements are done with the minimum external signal power [8]. We think that this discrepancy has its origin in the low frequency components described previously which are neglected in the calculation of the Josephson linewidth. When this remark is taken into account we have a reasonable agreement between the experimental points and theoretical results.

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$$\Delta f = \frac{\Delta\omega_0}{2\pi} = 2\pi \left(\frac{2e}{h}\right)^2 R_D^2 e \left[I_q \coth\left(\frac{eV_0}{2kT}\right) + 2 I_p \coth\left(\frac{eV_0}{kT}\right) \right].$$

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