# Broken-step Phenomenon in SIS Mixers

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*Abstract*— **In this paper, we discuss a "broken step" phenomenon in an SIS mixer. This phenomena was observed in the production version of the SIS mixers, designed for the 159-211 GHz RF band, being used for the construction of the ALMA Band 5 receiver The broken step typically appears at LO frequencies above 180 GHz and manifests itself as a sharp onset in the DC current at the middle of the quasiparticle step. Correspondingly, this affects the mixer IF response in a way that is similar to the Josephson step but is however of a different nature. Such behaviour affects the SIS mixer dynamic range and complicates the tuning of the 2SB mixer to optimize its performance, for both the receiver noise as well as the sideband rejection. In this paper, we describe results of a few experiments which were performed to understand this undesirable phenomenon.**

## INTRODUCTION

The broken-step was observed in the SIS mixers used for ALMA Band 5. When studying this phenomenon, we used the production version of the ALMA Band 5 2SB mixer, optimized for the 159-211 GHz RF band and largely based on the 2SB SIS mixer presented in [1] and data-acquisition software [2] specifically modified for the ALMA Band 5 project. The broken step appears typically at LO frequencies above 180 GHz and manifests itself as a sharp break in the DC current at the middle of the quasiparticle step. Correspondingly, this affects the mixer IF response in a way that is similar to a Josephson step but however is of a different nature. Such behaviour affects the SIS mixer dynamic range and complicates the tuning of the 2SB mixer for achieving optimum performance, for both the receiver noise as well as the sideband rejection. In this paper, we describe several diagnostic measurements performed on the receiver in order to isolate the root cause and physical origin of this phenomenon.

## SHAPIRO VS. FISKE VS. PHOTON STEP

The mixer was operated under different conditions (of bias voltage, LO pumping level, magnetic field), and physical temperatures in an attempt to establish if this phenomenon was related to the Josephson effect (Shapiro steps), or to internal resonances of the SIS mixer tuning circuitry (Fiske steps) or if it was a manifestation of some other mechanism. By varying the magnetic field and achieving accurate suppression of the Josephson effect, we ensured that this phenomenon has no coupling to the Cooper-pair current. For the given ALMA Band 5 mixer, which uses twin-junction tuning structure [3], the standard sin(x)/x pattern is modulated by SQUID-type dependence of critical current vs. magnetic field of the twin-junction. This calls for careful and precise tuning of the magnetic coil currents for each mixer of the 2SB assembly. Fig. 1 illustrates the IV characteristic (IVC) and the IF response (the IF power was the power integrated over 600 MHz bandwidth centred at 6 GHz IF ***in all figures below***) for the mixer with adjusted magnetic field to suppress Josephson effect. The "broken step" effect is clearly visible at the first photon step (marked by dashed line arrow) while the mixer IF response demonstrates no signs of the Josephson steps.

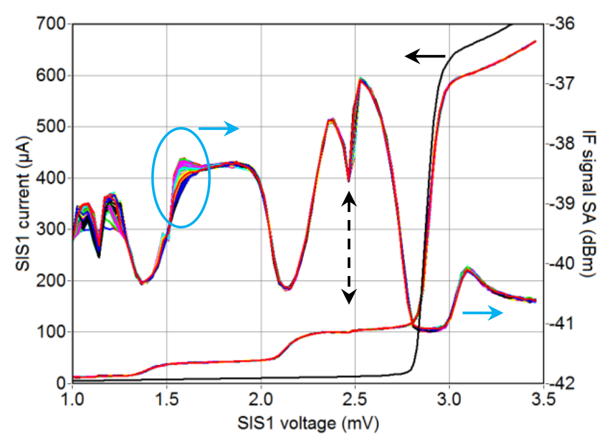


Fig. 1. Illustration of the magnetic field tuning (no visible signs of the Josephson steps affecting the IF response). The mixer IF response curve(s) indicate the IF power vs. DC bias voltage. The blue oval shows the area on the IF response where the Josephson step affects the performance and curves with different colours correspond to different magnetic field. The black and red lines show autonomous and pumped measured IVC. The "broken step" phenomenon at IVC and in the mixer IF response is marked by a dashed line arrow.

In order to completely exclude the effect of the Josephson steps or a Fiske step (the latter is unlikely as the corresponding frequency of the resonance would be around 2.2 THz), the mixer measurements were performed at several physical temperatures. The measurement setup allowed for a controlled variation of the physical temperature of the mixer between 3.4 K and 5.5 K and stabilisation at any selected temperature in this range. Fig. 2 shows the mixer IF response and the SIS mixer IVC at different physical temperatures as a function of the SIS junction gap voltage. The movement of the broken step feature is correlated with the junction gap voltage, This is indicative of the quasiparticle nature of the phenomenon and rules out internal resonance (Fiske step). This also excludes Shapiro step related origin of the observed broken step phenomenon, as it would not be dependent on temperature and as the Shapiro step-voltage counts from zero voltage.

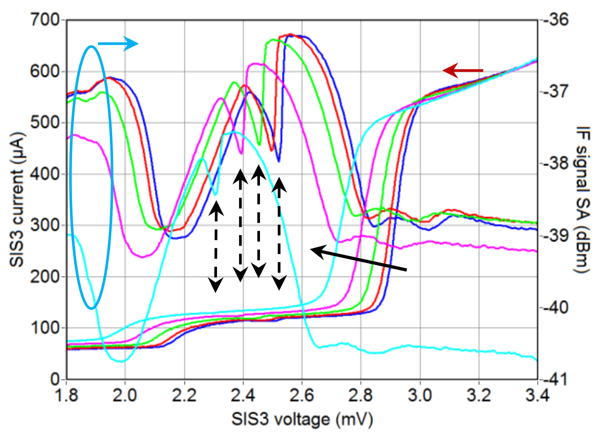


Fig. 2. The mixer IF response curves marked by blue oval shows the vs. DC bias voltage and the SIS IVC measured at different physical temperatures that is seen by the change of the SIS junction gap voltage (black arrow around 2.8 mV bias). The broken step feature moves along with the junction gap voltage, indicated by the black dashed arrows around 2.4 mV bias.

Our experiments strongly indicate that the broken step phenomenon is not coupled to Josephson effect (steps and internal resonances) but must be related with the quasiparticle tunnelling.

## Photon Steps from Two Strong RF Signals

Presence of a series of such broken steps observed on the tested SIS mixers lead us to conclusion that a fairly strong spurious RF signal must be incident on the SIS junction along with the LO frequency. Fig. 3 shows the measured IVC and the IF response of the SIS mixer with multiple "broken step" phenomenon that manifests itself at the first and second photon steps of the LO signal with the period of the half the LO photon step.

The above measurements indicate presence of two signals withdifferent frequencies. One of them is the LO while another could be half the LO frequency. This would yield two sets of the photon steps, as observed in the experiment. Simulations indicate that such dual-frequency operation resembles the observed "broken-step" phenomenon. Interestingly, the broken-step feature also appears in the pumped IVC for the case when signals with frequencies equal to the LO and 3/2 of the LO frequency are applied to the junction. To illustrate this, simulations were carried for the case of combinations of frequencies applied to the mixer SIS junctions. By varying the normalized pumping amplitudes, e.g., $\alpha_{91.5}$ & $\alpha_{183}$ and $\alpha_{183}$ & $\alpha_{274.5}$, it was possible to reproduce the "broken-step" feature with the predicted characteristic very close to what was observed during the measurements.

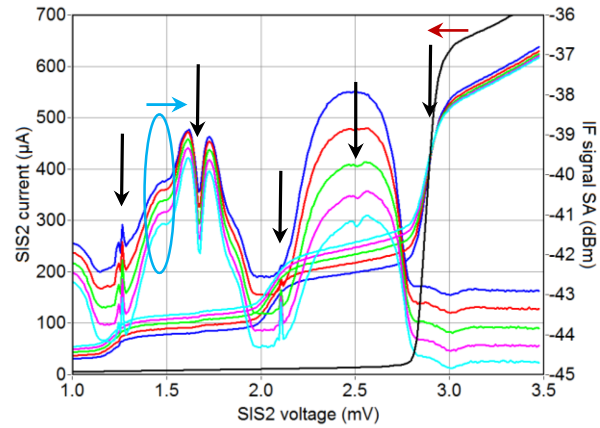


Fig. 3. The measured IVC and the IF response of the SIS mixer (marked by blue oval) with multiple "broken step" phenomenon that manifests itself at the first and second photon steps of the LO signal. It is clear that the scale of the broken-step phenomenon is half of the photon steps induced by the LO signal.

Fig. 4 and 5 show the simulated dual-frequency pumping: the experimentally measured IVC was used and signals were applied in sequence, e.g., obtain photon steps from one frequency and then use the already "stepped" IVC to apply the next frequency. The standard expression for calculating SIS junction IVC with applied RF signal, equation (1) below from [4] was used. The simulations were made using the data acquisition and calculation software IRTECON [2].

$$I(V)=\sum_n\sum_k J_n(\alpha_1)J_k(\alpha_2)I_{dc}\left(V+\frac{n\hbar\omega_1}{e}+\frac{k\hbar\omega_2}{e}\right),\ \text{where}\ \alpha=\frac{eV_\omega}{\hbar\omega}\quad(1)$$

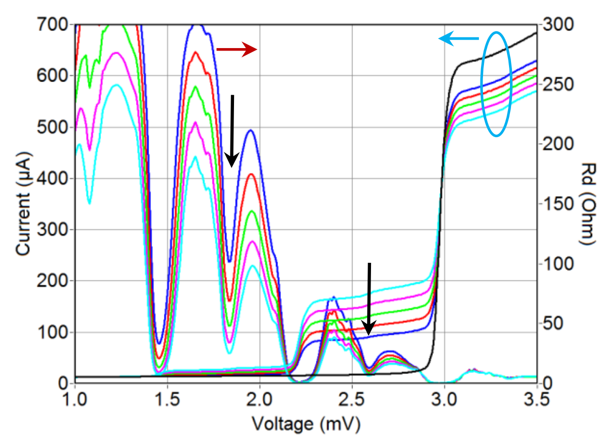


Fig. 4. Simulation results: The SIS mixer IVCs were measured through IRTECON, and were then modelled with the applied pumping signals with frequencies of 91.5 GHz and 183 GHz having different normalized pumping amplitudes, $\alpha_{91.5}$ and $\alpha_{183}$ (marked by blue oval). The differently coloured lines correspond to the different LO pumping, $\alpha_{183}$=0.7…1.1. The IVC differential resistance, $R_d$ was used as an indicator for the "broken-step" appearance. The "broken step" phenomenon at IVC and the $R_d$ is marked by arrows.

The figures above, show the non-pumped SIS mixer IVC measured through IRTECON, which was then modelled to have different values of the pumping RF signal applied to have photon steps of 91.5 & 183 GHz (Fig. 4) and 183 & 274.5 GHz signals (Fig. 5). The values for parameter $\alpha_{91.5}$ & $\alpha_{183}$ and $\alpha_{183}$

& $\alpha_{274.5}$ were adjusted to get the best fit. The first derivative of the pumped IVCs (differential resistance) was used as an indicator for the "broken-step" appearance.

It should be noted that the actual value of the pumping parameter α usually depends on the bias voltage for well-tuned SIS mixer. This is a function of the built-in on-chip integrated tuning circuitry of the SIS mixer and the embedding impedance, which is result of, e.g., the accuracy of the mixer chip placement inside the mixer block and the mixer block fabrication accuracy. In the simulations, we ignored the dependence of the parameter α on the DC bias voltage, which results in a slight difference between the simulated and measured IVC (Figure 3 vs. 4, 5) and its relative pumping levels at the second and the first photon steps.

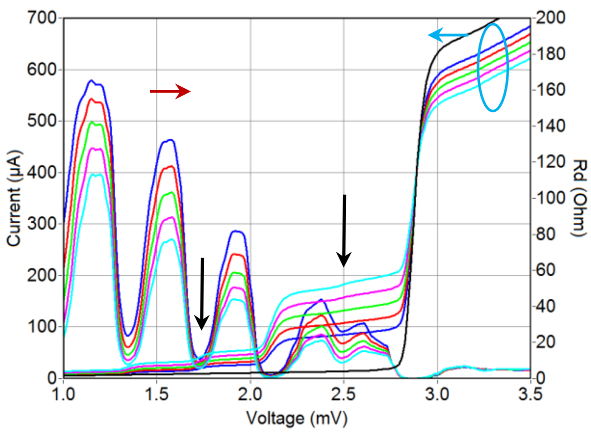


Fig. 5. Simulation results: The SIS mixer IVCs were measured through IRTECON, and were then modelled with the applied pumping signals with frequencies of 183 GHz and 274.5 GHz having different normalized pumping amplitudes, $\alpha_{183}$ and $\alpha_{274.5}$ (marked by blue oval). The differently coloured lines corresponds to the different LO pumping, $\alpha_{183}$=0.7…1.1. The IVC differential resistance, $R_d$ was used as an indicator for the "broken-step" appearance. The "broken step" phenomenon at IVC and the $R_d$ marked by arrows.

## DISCUSSION

From the described measurements and simulation, it can be concluded that the "broken-step" phenomenon is explained by the appearance of spurious RF signals in addition to the LO. The spurious signals could be half of the LO frequency at the SIS junction mixer or a frequency that is 3/2 times the applied LO frequency. If we consider the last multiplier stage of the LO, the frequency doubler, then the simulations indicate a combination of frequencies across the SIS mixer which are the doubler pumping tone (x1), x2 and x3 the pumping frequency.

It is extremely unlikely that a strong signal with 90-95 GHz appears directly at the Band 5 SIS mixer junction since this frequency is substantially below the cut-off frequency of the mixer LO port waveguide (dimensions are close to WR-5). Besides, the 2SB mixer has a relatively complicated waveguide configuration at its RF port (3 dB RF hybrid) and the LO port with a power divider and the LO injection coupler, all employing the WR5 waveguide circuitry [1]. Consequently, it is difficult to visualize a path for significant amount of the LO sub-harmonic to propagate to the mixer. Additionally, this frequency is unlikely to be leaking from the LO: it corresponds to the pump frequency of the final doubler in the LO chain, and cannot couple into the WR5 waveguide output of the doubler.

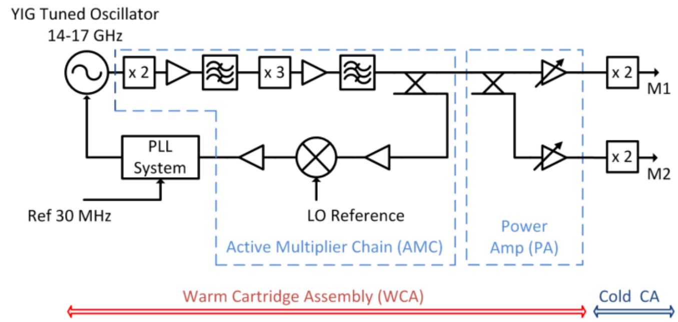


Fig. 6. Simplified block diagram of the ALMA Band 5 LO system that includes the warm cartridge assembly (WCA) and the cold cartridge assembly (CCA). M1 and M2 outputs in Fig. 6 indicate LO output to the Pol0 and Pol1 mixer assemblies.

Another possibility, which could be invoked to explain the appearance of the 90-95 GHz frequency signal is via the down-conversion of the second and third harmonic products generated at the final x2 multiplier stage of the LO source, i.e., the third harmonic around 270-285 GHz of the pump signal and the LO frequency around 180-190 GHz. Simulations indicate that the IVC is sensitive to the pumping level of the low-frequency signal, for example in the Fig.4, the $\alpha_{91.5}$ is only 24% of the $\alpha_{183}$ value and this is sufficient to produce well-developed "broken-step" phenomenon. This possibility however requires that the SIS mixer should be also tuned for frequencies 90-95 GHz, a frequency range, which would otherwise be nearly short-circuited by the SIS junction intrinsic capacitance.

If we now consider the presence of the signals in the range 180-190 GHz (LO) and 270-285 GHz, this combination could produce the "broken-step" directly (Fig, 5) but also provides conditions conducive to enable the down-conversion as discussed above, contingent on being complemented by "sensitivity band" of the SIS mixer itself. Both the down-conversion option and direct interaction with the third harmonic of the doubler pumping frequency in the presence of the LO (x2 pumping frequency) requires that SIS mixer is sensitive in this frequency band, 270-285 GHz.

One of the main factors affecting the SIS mixer sensitivity band is the integrated on-chip tuning circuitry. In usual design optimization procedure, the SIS mixer's built-in tuning circuitry is constructed to provide optimum SIS junction matching within a specified frequency band, which, in the case of ALMA Band 5 is 158-211 GHz, with some margins, typically 10-15% at the band edges. Simulations of the Band 5 SIS mixer tuning circuitry above 250 GHz indicate that some sensitivity, about -9 dB less than of the operational band, is possible and analysis points towards the RF/IF&DC isolation circuitry on the mixer chip. However, this simulation does not take into account the E-probe coupling with the waveguide. An accurate simulation is rather complicated by the fact that at the frequency above 225 GHz the mixer mount waveguide is not operated in the single-mode.

Another factor to consider is the relative strength of the third harmonic at the output of the LO doubler. In the ALMA Band 5 production project, the output of the multiplier was qualified for the unwanted harmonics and the output of the balanced diode doubler demonstrated to be better than -20 dBc, with measured values being closer to -25 to -30 dBc. Fig. 7 shows the results of such a screening measurement performed at room temperature.

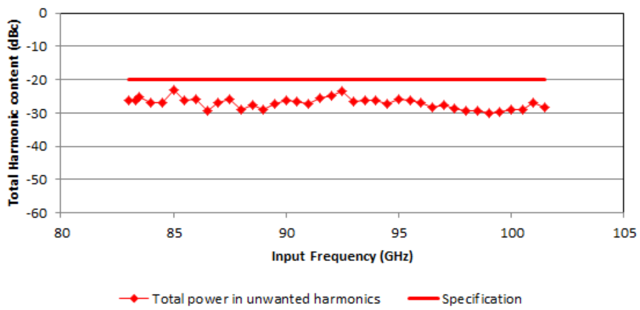


Fig. 7. Measured total power of the unwanted harmonics (x3 and above) at the output of the doubler WR5.1x2.

In light of all of the various arguments described above, interaction with the third harmonic from the LO doubler appears to be the only plausible explanation for the observed broken step phenomenon. This conclusion is supported by the results of the simulation (Fig. 5) and the modelling of the junction tuning circuitry. Further screening of the harmonic content at the output of the LO doubler and studying the correlation of the strength of the broken step phenomenon with the measured third harmonic strength in the multiplier output by measuring multiple instances of Band 5 cartridges would help definitively resolve the question..

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