Josephson Pair Tunnelling Influence on the Performance of an SIS Mixer near its Superconducting Gap

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Abstract: We report the investigation of the influence of Josephson pair tunnelling on the sensitivity of an SIS mixer near the superconducting gap of niobium. Hot and cold load measurements were carried out from 600 *GHz* to 700 *GHz*, without completely supressing the Josephson effect. We have noticed that when measurements were made at bias points near the first Shapiro step, significantly higher values of Y-factor could be obtained with magnetic field strengths that made the Shapiro step sharper, rather then those that supressed the step. This resulted in a significant improvement in noise temperature of the mixer at those bias points. This observation is important for SIS mixers operating at frequencies near or above gap frequency (ω_{gap}) because the warping of the second negative photon step to the positive display side, narrowing down the bias voltage interval in which measurement of the Y-factor at the first photon step could be done.

Keywords: Superconductor-Insulator-Superconductor (SIS) mixers, Josephson mixers, Sub-millimetre astronomy, Shapiro steps, Sub-millimetre receiver

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1. Introduction

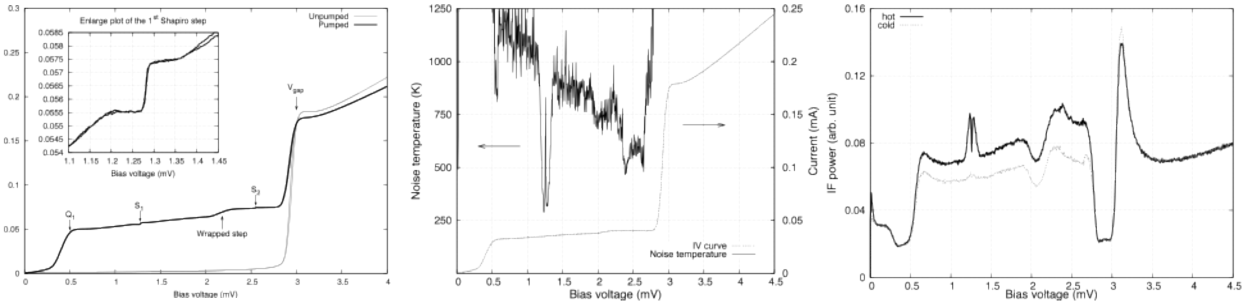
The quantum tunnelling effect across a thin insulating barrier between two superconductors has been employed extensively to design and fabricate ultra-sensitive coherent detectors for sub-millimetre wave astronomy. A tunnel junction can be configured to work as a Josephson mixer using the strong non-linearity of a Shapiro step that is formed by Cooper pairs tunnelling or as a photon-assisted tunnelling SIS mixer using the strong non-linearity in the quasi-particle (QP) density of states near the superconducting gap. When an SIS mixer is biased below the superconducting gap and is illuminated by an external RF source, both pair tunnelling and quasi-particles tunnelling can occur. Shapiro steps are formed at bias voltages given by $2eV_{sh} = nh\nu$ where e is the electron charge, ν is the signal frequency and h is Planck's constant; and photon steps have width given by $eV_Q = nh\nu$ measured from the gap. The SIS junction can therefore be modelled as two current sources, a Cooper pair current source connected in parallel to a quasi-particle current source, forming two mixers: a QP SIS mixer and a Josephson mixer working in parallel. Early work that has been carried out on both types of mixer demonstrated that QP SIS mixers are superior in performance (sensitivity and stability), to Josephson mixers. Josephson mixers were therefore abandoned and it became customary to suppress pair tunnelling when operating the QP mixers, by the application of magnetic field across the junction.

2. Description of the Mixer

The tunnel junctions in our mixers were fabricated from *Nb-AlO$_x$-Nb* that have a gap voltage (V_{gap}) of approximately 2.85 *mV* at 3.5 *K*, corresponding to a gap frequency of ~680 *GHz*. The mixer chip which includes the junction and the corresponding tuning and matching circuit were deposited on a 15 *μm* Silicon-On-Insulator substrate at KOSMA, University of Cologne. We employed a unilateral finline to couple the RF signal from the waveguide to the microstrip feeding the tunnel junction. The mixer was designed to operate in the frequency range of 600-700 *GHz* [1, 2], with a current density of 14 *kA*/*μm*. The sensitivity of the mixer was measured using the hot (297 *K*) and cold (77 *K*) loads method to find the Y-factor. The measured noise temperature was significantly higher than expected, due to the larger than designed tunnel junction area, resulting in mismatch between the tuner circuit and the junction impedance. Nevertheless, this does not influence the investigation in this paper.

3. Photon Step Warping Effect on the IV Curve

Fig. 1 (a) shows the pumped and unpumped current-voltage (IV) curves of the SIS mixers irradiated with a 634 *GHz* LO source. The Cooper pair nonlinearities (Shapiro steps) and the quasi-particle nonlinearities (photon steps) are clearly seen in the pumped curve. The steps labelled as S_n are the Shapiro steps and they are labelled sequentially as they appear above the dc Josephson nonlinearity at 0 *V*. As we have stated previously they are separated in voltage by hν/2e (1.31 *mV* at 634 *GHz*), the energy of the photon divided by the charge of the carrier. The quasi-particles steps are labelled as Q_n and are numbered sequentially away from V_{gap}. Their spacing in voltage is hν/e (2.62 *mV* at 634 *GHz*), twice as large as Shapiro steps spacing since the quasi-particle carrier charge is half of that of the Cooper pair. When operating at 634 *GHz*, there is only one quasi-particle step and two Shapiro steps below V_{gap}. The Cooper pair current is very sensitive to magnetic field strength, whereas the quasi-particle current is less influenced by it. Hence, in normal operation, magnetic field is applied to control the amplitude of the Cooper pair tunnelling, since near ω_{gap} operation the SIS junction becomes hysteretic. This issue is less critical when the mixer is operated well below ω_{gap}.



(a) (b) (c)

Fig. 1 IV curve showing the step warping, the Shapiro steps and the photon steps at 634 GHz. Figure (b) plots the noise temperature calculated using the IF curves displayed in figure (c).

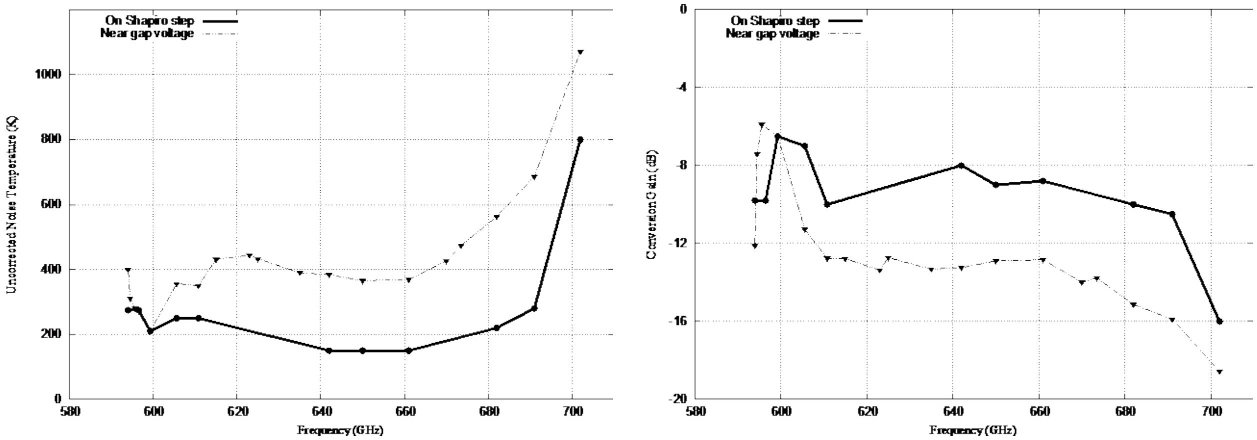
The existence of a dip in the pumped IV curve shown in Fig. 1 (a) at bias voltage of 2.2 *mV* reflects the warping of the second photon step from the negative to the positive side of the display. In other words, the display of the actual first photon step is reduced to bias voltages between the location of the dip and V_{gap}, while the rest is the overlap of the first-order photon step of the positive voltage region with the second-order photon step of the opposite negative voltage region [3]. This effect would be less noticeable if the LO power is insufficient to excite the negative higher-order photon steps, and at frequency significantly lower than ω_{gap}, as the negative higher-order photon steps would remain at the opposite voltage region. Clearly, the best noise temperature values are obtained at bias voltage across the first photon step region, which can also clearly be seen from Fig. 1 (b) and (c). However, the step warping effect becomes more restrictive as the operating frequency approaches or above ω_{gap}. The negative second photon step would be entirely coinciding with the positive first photon step, reducing the unsuppressed first positive photon step region to negligible width. Moreover, a Shapiro step occupies the centre of this narrow region makes it even harder to obtain a clean measurement on the first photon step without degrading the mixer by the application of a strong magnetic field.

4. Effect of Josephson Current on SIS Mixer Operation

In an ideal QP mixer, the Josephson current is fully suppressed by the external magnetic field. In that case, the best performance of the SIS mixer is obtained at dc bias points near the V_{gap} on top of the first photon step. Fig. 1 however shows that the Josephson features cannot easily be suppressed and unexpectedly, we notice that the noise temperature measured near the first Shapiro step (S_1) is actually better than at bias points near V_{gap}. We attribute this effect to the incomplete suppression of Josephson current, which under carefully chosen parameters enhances the mixing performance.

We further measured the noise temperature at bias point near S_1 and near V_{gap} across the designated waveband of the mixer, from 600-700 *GHz*. As shown in Fig. 2, the improvement in noise temperature measured near S_1 is obvious. As indicated before, due to the larger than designed junction size, the performance of our mixer is only markedly better at lower end of the frequency band, with the best noise temperature measured at 600 *GHz*. Below this frequency, our LO lacked enough power to pump the mixer to a sufficient level for proper noise temperature measurement. Nevertheless, at this frequency, there is no significant improvement in the noise temperature measured at both bias points.

This behaviour of enhancing mixing performance near S_1 seems to indicate that the tunnel junction is now behaving as a dual-charge-carrier mixer where the QP SIS mixer working in parallel with a Josephson mixer, in which both are operating at their optimum biasing point. The mixing is now occurring through both the Cooper pair and the quasi-particle tunnelling. If the Josephson mixer could be removed completely by suppressing pair tunnelling and the noise temperature of the QP mixer could be measured at the first photon step, the operation of a single QP mixer is certainly superior. If on the other hand, Josephson tunnelling could not be completely suppressed, it will inevitably contribute to the receiver noise. In that case, optimising the pair tunnelling signal can improve the QP mixers performance, in particular relative to the noise temperature measured at the warped photon step region.



(a) (b)

Fig. 2 Multitude of the noise temperature improved by comparing the noise temperature measured at the first Shapiro step and the conventional bias point near the gap voltage. It is clearly seen that when the real first photon step is not available at higher frequencies end, the Shapiro steps measurement has a factor of $\sim \nu'^2$ improvement.

Effects similar to this behaviour have been reported previously [4], [5]. Vystovkin et. al. [4] noticed that the mixer conversion gain measured using the hot and cold technique was highest near the Shapiro step regions. They confirmed their observation by replacing the Y-factor measurement by directly injecting two LO signals into the tunnel junction to perform coherent measurement. However, Wrengler et. al. [5] argued that the Y-factor measurement in this case is misleading and the Josephson pair tunnelling should always be suppressed. They also supported their claim using coherent measurements.

5. Conclusions

We have reported the observation of the enhancement of the measured gain of an SIS mixer operating near the superconducting gap, when the Y-factor was measured near a Shapiro step. This observation was persistent when it was difficult to suppress the Josephson effect completely and when step warping combined with Josephson features do not allow measurement of the Y-factor on the first photon step. This is contradictory to the conventional operation of quasi-particle mixer where measurements near the Shapiro steps are always avoided. Two investigators have encountered this effect but came to opposite conclusions. We plan to further investigate this observation by using spectroscopic measurement in conjunction with a gas cell.

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