Multi-Tone Spectral Domain Analysis of a 230 GHz SIS Mixer

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***Abstract*—We present a new software package for simulating the performance of Superconductor / Insulator / Superconductor (SIS) mixers. The package is called QMix (“Quasiparticle Mixing”) and it uses multi-tone spectral domain analysis (MTSDA) to calculate the quasiparticle tunneling current through the SIS junction. This technique is very powerful and it allows QMix to simulate multiple strong tones and multiple higher-order harmonics. We have compared this software to the experimental data from a 230 GHz SIS mixer, both to validate the software and to explore the measured results. Overall, we found very good agreement, demonstrating that QMix can accurately simulate the performance of SIS mixers. We believe that QMix will be a useful tool for analyzing experimental data, designing new SIS mixers, and simulating new applications for SIS junctions, such as frequency multiplication.**

***Index Terms*—Superconductor / Insulator / Superconductor (SIS) mixer, simulation software, millimeter-wave receivers, superconducting detectors**

We have developed a new software package for simulating the behavior of Superconductor / Insulator / Superconductor (SIS) mixers. The package is called QMix [1], short for “Quasiparticle Mixing”, and it is now freely available online. The software package is currently hosted on the Python Package Index [2] and GitHub [3] under an open-source license (GNU General Public License v3), meaning that anyone is free to download, modify, distribute and utilize the software. Other researchers are also welcome to add new features to the QMix package by contributing to the GitHub repository.

The QMix software is based on multi-tone spectral domain analysis (MTSDA) [4-7]. To summarize, when a signal is applied to an SIS junction, it modulates the quasiparticle energy eigenstates on the ungrounded side by a phase factor. Using MTSDA, we convolve the phase factors from each signal applied to the mixer in the spectral-domain in order to calculate the total phase factor of the quasiparticles. This is then used to calculate the time-averaged tunneling current through the SIS junction, from which we can calculate the output power and the conversion gain of the mixer. (This technique is described in detail by [6, 8].)

Unlike other simulation methods, which normally use perturbation techniques, MTSDA can simulate multiple strong non-harmonically related frequencies and an arbitrary number of higher-order harmonics. Therefore, we can use QMix to simulate a wide variety of SIS mixer behavior, such as the effect of higher-order harmonics in the LO signal and gain saturation as a function of RF signal power. Beyond heterodyne mixing for radio astronomy, QMix can also simulate other applications for SIS junctions, including frequency multiplication [9] and potential high-frequency communications systems.

In order to validate the software, we compared QMix simulations to experimental data from a 230 GHz SIS mixer. This was also done as a means to analyze the experimental results. The SIS device that we used for this comparison has already been presented in [8]. It is a single-ended device that uses a finline to couple the RF+LO signals to the planar circuit, and it has a 1.5 μm^2 Nb/Al/AlO_x/Nb junction with tuning structures on either side to tune the capacitance of the junction across a wide RF frequency range (140—270 GHz). We have tested this device extensively [8] and it has provided noise temperatures down to 35 K at frequencies around 230 GHz.

We setup a QMix simulation specifically to recreate the experimental results from the 230 GHz SIS mixer. This simulation included 4 different tones: the local-osciallator (LO) frequency, the upper sideband (USB) frequency, the lower sideband (LSB) frequency, and the down-converted intermediate frequency (IF). Since this is a double-sideband (DSB) mixer, we applied equal input power to both the upper and lower sidebands. We also included 2 higher-order harmonics for each tone.

To run the QMix simulation, the software required: (a) the embedding circuit for each unique frequency that was applied to the mixer, and (b) the response function of the SIS junction. For (a), we simulated the planar circuit using electromagnetic simulation software. Since the planar circuit is entirely linear it can be reduced to a Thevenin equivalent circuit with one circuit for each individual signal. For (b), we used the measured DC current—voltage relationship of the junction (i.e., the DC I-V curve) to generate the imaginary component of the response function, and then we used the Kramers-Kronig transform of the DC I-V curve to calculate the real component.

We then simulated the conversion gain of the SIS mixer at different LO frequencies using the QMix software. In Fig. 1, we compare the simulated results to the experimental data from the SIS mixer at 225.0 GHz. There is very good agreement between the simulated and experimental results, suggesting that QMix accurately modeled the behavior of the SIS mixer.

When we tested this device, the experimental results displayed “broken photon steps” at frequencies between 236 GHz and 255 GHz. This effect is characterized by a notch in the pumped I-V curve and a sharp decrease in conversion

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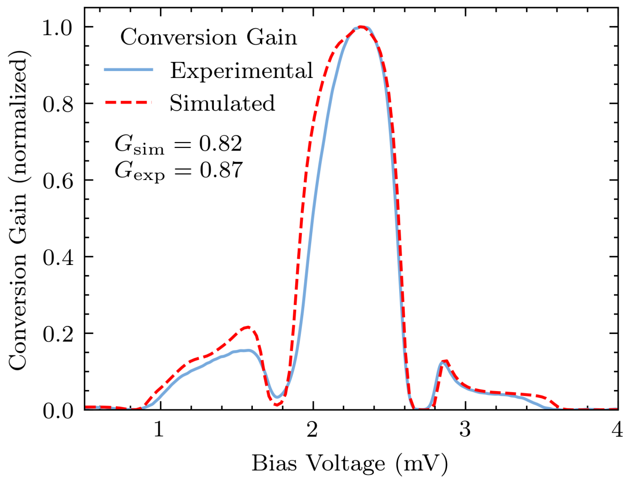

Fig. 1. The conversion gain of the SIS mixer at 225.0 GHz. The simulated results from QMix are shown in red, and the experimental results are shown in black. Both curves are normalized to their maximum values, which are listed below the legend.

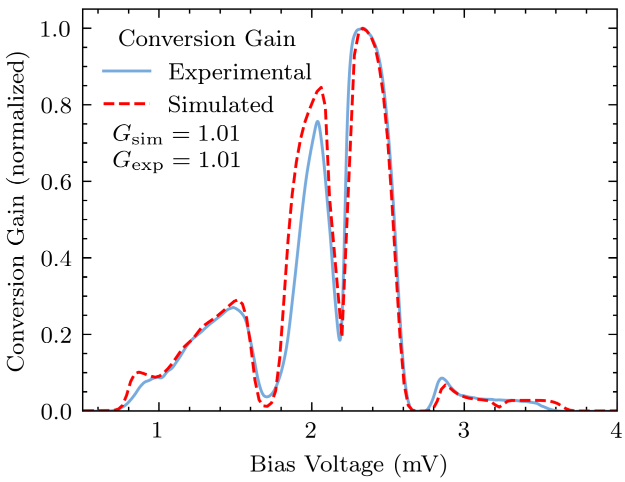

Fig. 2. Simulating the broken photon step effect at 240.5 GHz with the QMix software. This effect is characterized by a sharp decrease in conversion gain in the middle of the first photon step (at ~2.2 mV). We were able to recreate this effect with QMix by adding a spurious harmonic to the LO signal at $\frac{3}{2} f_{LO}$.

gain in the middle of the first photon step. Ermakov *et al.* [10] investigated this phenomenon and suggested that it could be caused by a spurious harmonic from the local-oscillator at either $\frac{1}{2} f_{LO}$ or $\frac{3}{2} f_{LO}$, where f_{LO} is the LO frequency. Since $\frac{1}{2} f_{LO}$ is below the waveguide cutoff for this device we added a spurious harmonic at $\frac{3}{2} f_{LO}$ to the QMix simulation. The results are shown in Fig. 2 and again there is very good agreement between the simulated and experimental results, supporting the work of Ermakov *et al.* [10]. Based on these findings, we should filter the harmonics from the LO source to reduce the severity of the broken photon step effect. Overall, this example demonstrates how QMix can be used to investigate the experimental results from SIS mixers.

In conclusion, we have presented a new software package called QMix for simulating SIS devices. The software is based on MTSDA, which allows QMix to simulate multiple harmonics and multiple strong frequencies. We have compared the simulated results from this software to the experimental data from a 230 GHz SIS device. We found very good agreement, demonstrating that the software can accurately model the SIS mixer's behavior. We are now applying the software to design new SIS mixers and simulate new SIS applications, such as frequency multiplication. All of the QMix software is open-source and we invite other researchers to use the software and contribute to the project.

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