Spectral Domain Simulation of SIS Frequency Multiplication

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Abstract— In this paper, we compare simulations to experimental results for a new SIS frequency multiplier. To simulate these devices, we developed software based on spectral-domain analysis, which is ideal for simulating higher-order harmonics such as those present in a multiplier. In addition, we included the embedding circuit and interpolated the experimental I-V curve to allow the simulation to capture the experimental system as closely as possible. For the experimental data, results were taken from a new SIS frequency multiplier that has recently been developed at the Chalmers University of Technology. Previously, these experimental results were compared to simulations based on Tucker theory. Here, we compare these results to spectral-domain simulations. Qualitatively, the inclusion of embedding impedances and the use of spectral-domain analysis improves the agreement between simulation and experiment. The software can now be used to design multipliers with high output power and high conversion efficiency.

INTRODUCTION

The nonlinear behavior of quasiparticle tunneling in superconductor-insulator-superconductor (SIS) junctions is ideal for creating mixers and frequency multipliers. Frequency multipliers created from SIS junctions have many potential benefits including improved conversion efficiency and creating on-chip multipliers. These benefits will become even more important as superconducting receivers are pushed to higher frequencies.

Recently, the Chalmers University of Technology has developed new distributed SIS frequency multipliers (DSMs, [1-3]). The name comes from their elongated shape (1 um x 20 um), which helps to reduce the effect of the junction's intrinsic capacitance. Compared to frequency multipliers that use arrays of SIS junctions in series, DSMs do not have the same problems with local heating and harmonic intermixing.

In [1] and [2], experimental results from a DSM were compared to Tucker theory [4] with good agreement. In this work, we hope to expand upon these advances by comparing experimental results to spectral-domain simulations that include the complex embedding impedance for each harmonic.

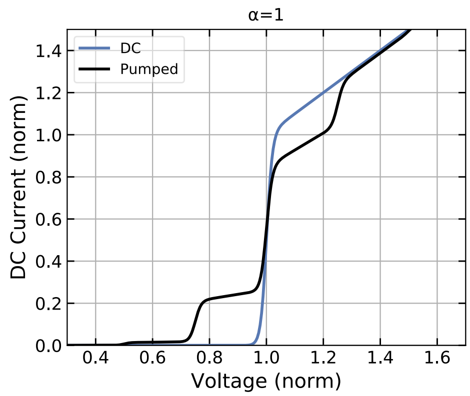
SIS MULTIPLIER SIMULATION

Tucker theory [4] provides a quantum mechanical model of SIS mixer operation. Typically, when this theory is applied however, the local-oscillator signal is assumed to be purely sinusoidal with all higher-order modes short-circuited by the junction's intrinsic capacitance. This is only accurate when the ωRC product is less than ~4 [5]. Since the goal of this work is to simulate the higher-order currents, we must use a different technique to simulate the tunneling current.

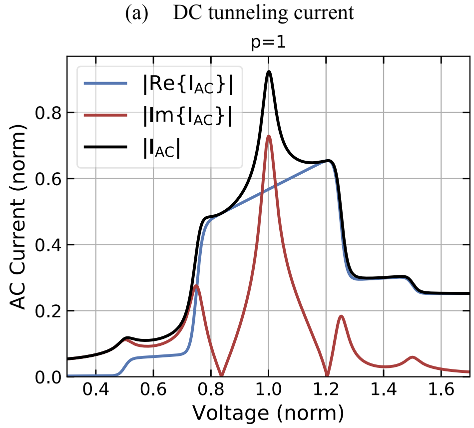
With this in mind, we developed a software package based on spectral-domain analysis [5] at the University of Oxford. The spectral-domain technique calculates higher-order harmonic currents without assuming anything about the junction's properties. In addition, this technique can include complex embedding impedances and solve the resultant nonlinear circuit using harmonic balance. We also added several other features in order to recreate experimental data as closely as possible. This includes the ability to import and interpolate experimental I-V curves to fully capture the junction's properties (e.g., subgap current, transition linearity, proximity effect, etc.). We wrote the software package in Python with heavy use of the Numpy library, making it fast, flexible and portable to other systems.

SIMPLE MULTIPLIER SIMULATION

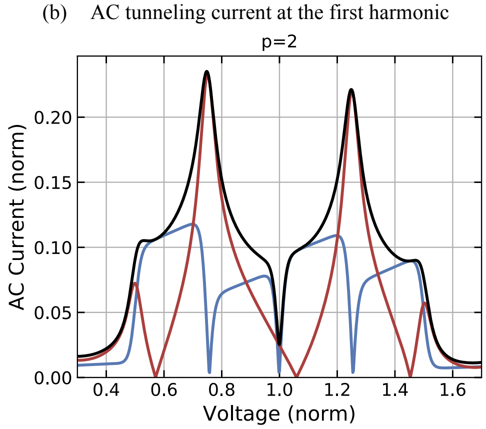
As a basic demonstration of the software, we simulated the AC quasiparticle tunneling current for the first two harmonics (Fig. 1). The frequency of the local-oscillator (LO) signal was set to one quarter of the gap frequency, i.e., $\tilde{V}_{ph} = 0.25$ where $\tilde{V}_{ph}$ is the normalized photon voltage. The junction drive level was set to $\alpha = \tilde{V}_J/\tilde{V}_{ph} = 1$ where $\tilde{V}_J$ is the normalized voltage applied across the junction. For the sake of keeping the simulation simple, no embedding circuit was included and therefore no harmonic balance was needed. All currents and voltages in Fig. 1 are normalized to the gap voltage v_{gap} and normal resistance R_N of the junction.



(a) DC tunneling current



(b) AC tunneling current at the first harmonic



(c) AC tunneling current at the second harmonic

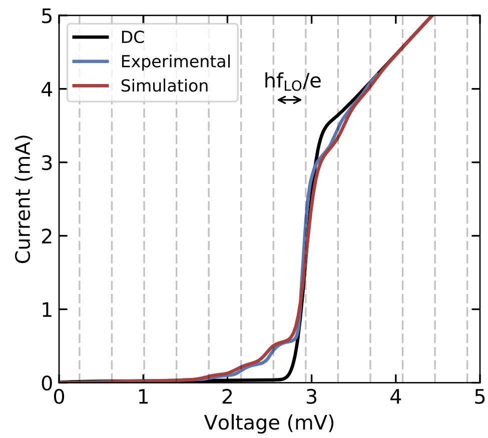
Fig. 1 Simulated tunneling current in a simple SIS frequency multiplier.

The current of the second harmonic is seen in Fig. 1c. This is the multiplied signal as its frequency is twice that of the original LO signal. Since power is proportional to $|I_{AC}|^2$, these simulations predict peak output power at a bias voltage equal to $1 - \tilde{V}_{ph}$ although this could change depending on the pump level and embedding circuit.

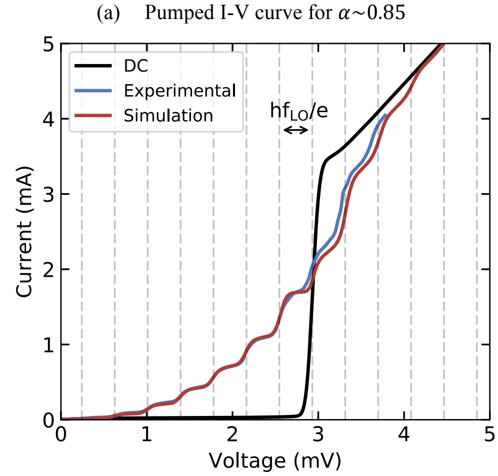
Comparison to Experimental Results

The experimental results in this section were previously reported in [1, 2]. They come from a DSM that has recently been developed at the Chalmers University of Technology. The experimental results include the DC I-V curve (both with and without the LO present) and the output power level at the second harmonic (i.e., the multiplied signal). These were measured for two different pump levels ($\alpha \sim 0.85$ and $\alpha \sim 3.0$) with the LO frequency set to 93 GHz.

From the experimental DC I-V curve, the gap voltage and normal resistance were found to be $v_{gap} = 2.93$ mV and $R_N = 0.81\ \Omega$, respectively. The embedding impedances were recovered by fitting simulations to the experimental pumped I-V curves (Fig. 2). For the first and second harmonic, the normalized impedances were found to be $Z_1 = 0.7 - j0.3$ and $Z_2 = 0.015$, respectively. To improve the matching, the characteristic I-V curves were rounded slightly. This was done by convolving the I-V curve with a Gaussian function.



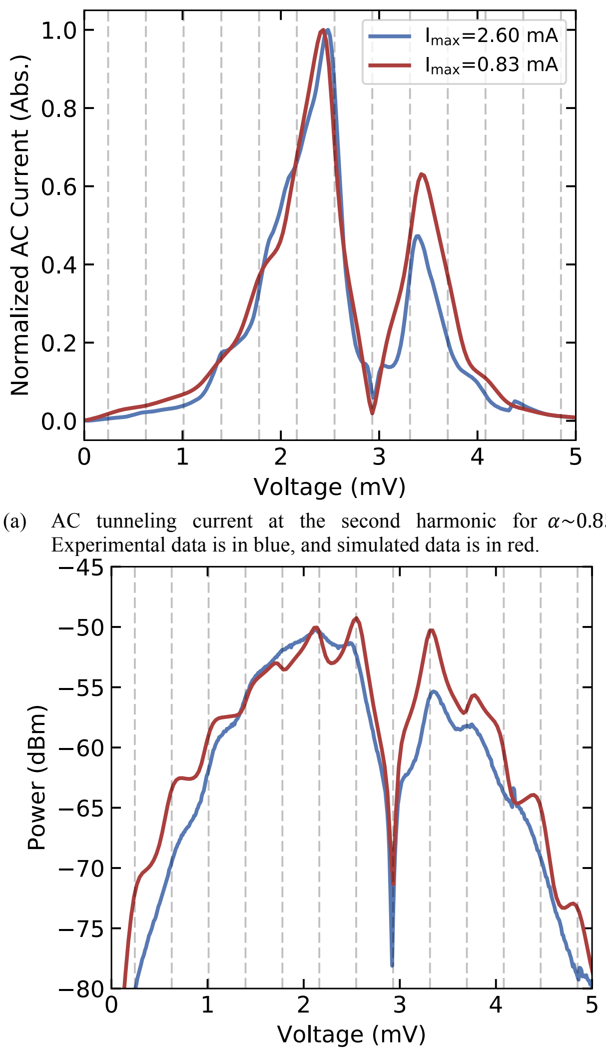
(a) Pumped I-V curve for $\alpha \sim 0.85$



(b) Pumped I-V curve for $\alpha \sim 3.0$

Fig. 2 Simulated DC tunneling current compared to experimental results.

With the embedding circuit and characteristic I-V curve, we were then able to simulate the higher-order AC currents present in the DSM. The results from the second harmonic are shown in Fig. 3. For $\alpha \sim 0.85$ (Fig. 3a), the shape of the output current is very close, but the results are offset by a scaling factor ~3. This is likely due to a different impedance being used to simulate the results from that which was used to de-embed the experimental results. For $\alpha\sim3.0$ (Fig. 3b), the simulation estimates the output power of the DSM much more accurately as well as the relationship to bias voltage.



(a) AC tunneling current at the second harmonic for $\alpha\sim0.85$. Experimental data is in blue, and simulated data is in red.

(b) AC power at the second harmonic for $\alpha\sim3.0$. Experimental data is in blue, and simulated data is in red.

Fig. 3 Simulated AC tunneling current at the second harmonic compared to experimental results.

The match between simulation and experiment could potentially be improved by simulating the DSM in electromagnetic simulation software (e.g., Ansys HFSS). This would allow the embedding impedances to be found through simulations instead of de-embedding the experimental pumped I-V curves. Furthermore, the impedance of higher-order harmonics (p>2) could be found which might affect the performance of the second harmonic. The match could also be improved by having more information about the experimental setup. For example, local-oscillators often emit many other frequencies apart from their fundamental tone. This is due to the LO multipliers generating high-order harmonics and allowing low frequency signals to leak through. Low frequency leakage can affect the shape of the I-V curve, and could be the reason the I-V curve needed to be rounded in Fig. 2.

Simulations of SIS Multiplier Efficiency

Since the power delivered to the junction and the power delivered to the load are known, conversion efficiency in this section will be defined as

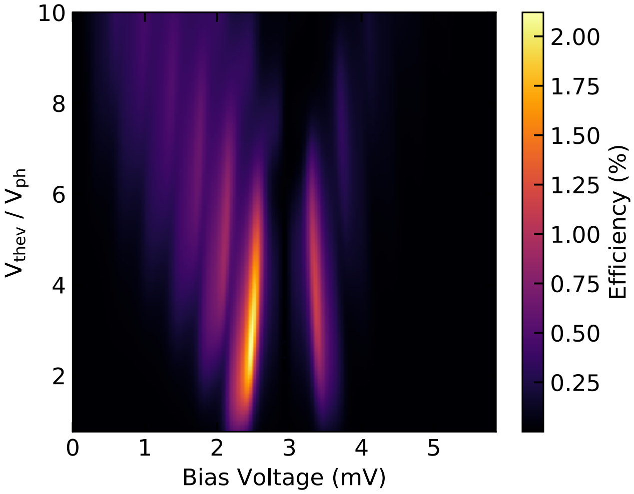
$$\eta = \frac{P_{L,p=2}}{P_{J,p=1}} \times 100\ \%$$

where $P_{L,p=2}$ is the output power delivered to the load at $f = 2f_{LO}$, and $P_{J,p=1}$ is the input power delivered to the junction at $f = f_{LO}$. In order to have a good understanding of where the maximum efficiency is found, the efficiency was calculated for a range of bias voltages and a range of input AC voltage amplitudes V_{thev}. The efficiency results using the embedding impedance values from the previous section are shown in Fig. 4a, while the efficiency using a different set of impedances ($Z_1 = 0.1$ and $Z_2 = 0.5$) is shown in Fig. 4b.

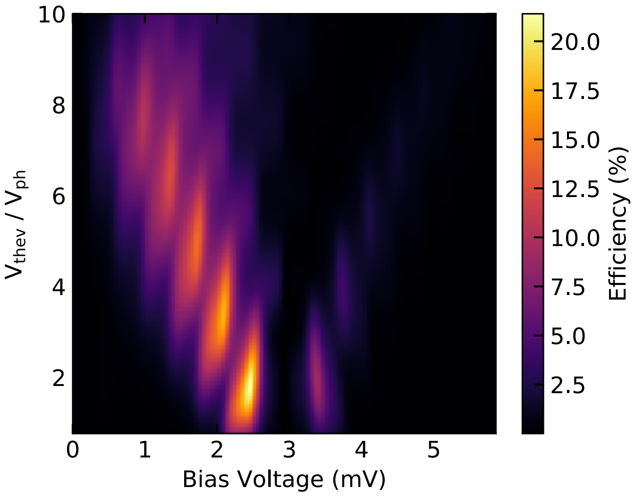
In both cases, the peak efficiency occurs at $\tilde{V}\sim1-\tilde{V}_{ph}$, similar to the simple simulation from Fig. 1. From Fig. 4a, we can see that the DSM was pumped near its maximum efficiency at $\alpha\sim3.0$ (Fig. 3b); although, more output power could be found above this level. Fig. 4b is included to show that conversion efficiency can be optimized by altering the embedding impedance. The embedding impedances used in Fig. 4b were chosen by hand. Higher efficiency can be found by optimizing these simulations. This will allow optimal performance SIS multipliers to be designed in the future.

Conclusions

We have compared spectral-domain simulations of an SIS frequency multiplier to experimental results. The simulation software was designed specifically to simulate higher-order harmonics, while the experimental results were taken from a distributed SIS multiplier. Good agreement between simulations and experimental results was found, suggesting that the simulation software is able to adequately capture the experimental system. The simulation software can now be used to design new SIS multipliers with high output power and high conversion efficiency.



(a) Simulated conversion efficiency for $Z_1 = 0.7 - j0.3$ and $Z_2 = 0.015$



(b) Simulated conversion efficiency for $Z_1 = 0.1$ and $Z_2 = 0.5$

Fig. 4 Simulated conversion efficiency of an SIS frequency multiplier.

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