

A Nonlinear Transmission Line Model for Simulating Distributed SIS Frequency Multipliers

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Abstract—Superconductor / Insulator / Superconductor (SIS) junctions have extremely nonlinear electrical properties, which makes them ideal for a variety of applications, including heterodyne mixing and frequency multiplication. With SIS mixers, the SIS junctions normally have circular cross-sections, but they can also be fabricated in the form of microstrip transmission lines, known as distributed SIS junctions (DSJs). By using a DSJ as an open-circuit stub, it is possible to create a large SIS junction with a low effective input reactance. This is beneficial for SIS frequency multipliers because their output power is proportional to the area of the junction. It is challenging, however, to simulate the behavior of DSJs because (a) they have to be modeled as transmission lines and (b) the model has to take into account the quasiparticle tunneling current, which is a nonlinear function of the AC voltage. In this paper, we present a new nonlinear transmission line model to accurately describe the behavior of DSJs and to simulate the performance of distributed SIS frequency multipliers (DSMs). This model is compared to experimental data from a recent DSM device and good agreement is found between the DC tunneling currents and the output powers at the second harmonic. Based on this success, an improved DSM design is proposed that has a higher output power and a higher conversion efficiency than previous designs.

Index Terms—Superconductor/Insulator/Superconductor (SIS) junctions, distributed SIS junctions, frequency multiplication, nonlinear transmission line models, terahertz receivers, superconducting detectors

I. INTRODUCTION

At millimeter and submillimeter wavelengths, radio telescopes use Superconductor / Insulator / Superconductor (SIS) junctions to build extremely sensitive heterodyne receivers. These receivers are now in widespread use and modern SIS mixers have noise properties that are only 2 to 3 times the quantum limit [1]–[3]. Current research is now seeking to develop SIS receivers that operate above 1 THz and focal plane arrays that allow multiple SIS receivers to observe

simultaneously. Both of these applications require powerful local-oscillator (LO) signals in order to drive the SIS junctions and efficiently down-convert the astronomical signals.

In most LO sources, the signal is initially generated by a synthetic signal generator, a Gunn diode or an yttrium-iron-garnet (YIG) oscillator. The frequency of the signal is then multiplied to the desired value, often in several stages, using nonlinear components. For example, the Atacama Large Millimeter Array (ALMA) Band-9 LO uses a $\times 3 \times 3 \times 3$ multiplier chain to produce a 600–720 GHz signal [2], [4] and the ALMA Band-10 LO uses a $\times 2 \times 3 \times 3 \times 3$ multiplier chain to produce a 792–945 GHz signal [4], [5]. (Both of these LO sources use YIG oscillators to generate the initial input signals.) With several cascaded frequency multipliers, it is then very important that each multiplier within the LO chain has a high conversion efficiency in order to produce an adequate output power for the SIS receiver. This is especially true for receivers that operate above 1 THz, which require additional frequency multiplication stages, and for focal plane arrays, which split the LO signal between multiple SIS devices.

Currently, most frequency multipliers use Schottky diodes to generate higher-order harmonics from sinusoidal input signals; however, recent research has proposed using SIS junctions instead [6]–[9]. Since SIS junctions have extremely nonlinear properties, these multipliers may be able to provide higher conversion efficiencies and operate at higher frequencies than Schottky diodes. SIS frequency multipliers also have the added advantage that they can be easily integrated with the SIS mixers inside the cryostat, which would reduce the complexity of the receiver and the loss in the LO signal path. For instance, in the current ALMA Band-5 receiver, the final frequency doubler is placed inside the cryostat on the 110 K stage [1], [4]. By using an SIS frequency multiplier, this component could be integrated with the SIS mixer on the 4 K stage, potentially even on a single chip.

The challenge with SIS frequency multipliers is that their output power is proportional to the area of the junction (assuming a constant tunneling current density). Unfortunately, the intrinsic capacitance of the junction is also proportional to the area, which could severely limit the bandwidth of the multiplier if it is not tuned sufficiently. To overcome this obstacle, SIS frequency multipliers were developed using arrays of smaller SIS junctions connected in series [6], but these multipliers suffered from local heating effects and inter-mixing between the harmonics. Rashid *et al.* [7]–[9] then reported a new frequency multiplier using distributed SIS junctions (DSJs), which are SIS junctions fabricated in the form of

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microstrip transmission lines. By using DSJs as open-circuit stubs, it is possible to reduce the effective input reactance, allowing DSJs to be much larger than circular junctions, while maintaining a favorable input impedance. Unlike series arrays, DSJs also do not encounter the same issues with heating and inter-mixing [6]–[9].

To simulate the performance of distributed SIS frequency multipliers (DSMs), Rashid *et al.* [7]–[9] presented a quasi-nonlinear transmission line model and compared it to their experimental DSM device. They found reasonable agreement, but the model did not take into account that the tunneling current and the propagation constant should change with position along the DSJ, depending on the magnitude of the AC voltage. To address this limitation, we now present in this paper a new fully nonlinear transmission line model, which should improve the accuracy of DSJ simulations. This model divides the DSJ into a series of segments that are small enough that the propagation constant can be assumed to be fixed over each unit length. It then uses spectral-domain simulation software to calculate the nonlinear response of the SIS junction and estimate the power generated at the second harmonic. In the following, the quasi-nonlinear model is reviewed in Sec. II, the new nonlinear model is presented in Sec. III, and then it is compared to experimental data in Sec. IV. Lastly, using the new nonlinear model, an improved DSM device is proposed in Sec. V, which has both higher output power and higher efficiency than current designs. In future work, we hope to fabricate this new DSM device and further validate the model by comparing it to additional experimental data. This initial paper will focus on the limitations of the quasi-nonlinear model and how these limitations are addressed by the new nonlinear DSJ model.

II. QUASI-NONLINEAR DSJ TRANSMISSION LINE MODEL

A diagram of a DSJ is shown in Fig. 1a. It is characterized by its width W and length L , as well as the thickness of the wiring, insulation and ground layers, represented by d_w , d_i and d_g , respectively. Although this DSJ has the form of a microstrip, the fringing fields are insignificant because $W \gg d_i$. Therefore, the DSJ can be modeled as a parallel-plate waveguide with an additional admittance term to represent the quasiparticle tunneling current.

The lumped-element equivalent circuit of the DSJ is shown in Fig. 1b [10]. In this model, the shunt capacitance C and the series inductance L per unit length are given by well-known equations for parallel-plate waveguides [11]:

$$C = \frac{\varepsilon_i W}{d_i} \quad (1a)$$

$$L = \frac{\mu_i d_i}{W} \quad (1b)$$

where ε_i and μ_i are the permittivity and permeability of the insulation barrier, respectively. Since the thickness of the insulation barrier d_i is not known precisely, the specific capacitance can be estimated using the empirical formula [12]:

$$C_s = \frac{0.3}{\ln(R_n \cdot A_J)} \quad (2)$$

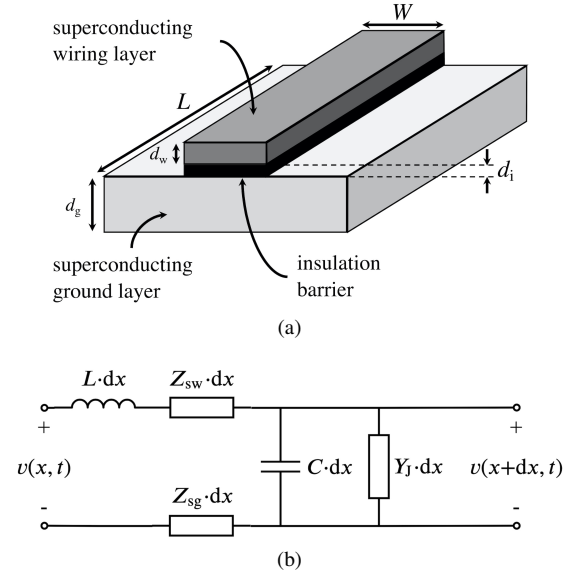


Figure 1. Modeling distributed SIS junctions (DSJs). A diagram of a DSJ is shown in (a) and the quasi-nonlinear transmission line model [10] is shown in (b). Here, L and C represent the inductance and capacitance per unit length, respectively; Z_{sw} and Z_{sg} represent the surface impedance of the superconducting wiring and ground layers, respectively; and Y_J represents the admittance of the quasiparticle tunneling current.

where C_s is in units $\text{pF}/\mu\text{m}^2$, R_n is the normal-state resistance in units Ω , and A_J is the area of the junction in units μm^2 . By combining Eqns. 1 and 2, this empirical formula can also be adapted to estimate the specific inductance:

$$L_s = \frac{\mu_i \varepsilon_i \cdot \ln(R_n \cdot A_J)}{0.3} \quad (3)$$

where L_s is in units $\text{pH}/\mu\text{m}^2$.

The surface impedance of the wiring and ground layers is represented in Fig. 1b by Z_{sw} and Z_{sg} , respectively. Since these layers are superconducting, Mattis-Bardeen theory [13] should be applied to estimate their values; however, for frequencies well below the gap frequency (below ~ 350 GHz for niobium), the surface impedance can be approximated by [14]:

$$Z_s = j\omega\mu\lambda_L \coth\left(\frac{d}{\lambda_L}\right) \quad (4)$$

where $j = \sqrt{-1}$ is the imaginary unit, ω is the angular frequency, λ_L is the London penetration depth and d is the thickness of the superconducting layer.

Finally, the admittance of the quasiparticle tunneling current is represented in Fig. 1b by Y_J . It is calculated by:

$$Y_J = \frac{I_\omega}{V_\omega \cdot A_J} \quad (5)$$

where V_ω is the AC voltage across the junction and I_ω is the consequent AC tunneling current. Both V_ω and I_ω are complex values. For I_ω , the real and imaginary components are calculated by the large-signal tunneling equation¹ [15]:

$$\text{Re}\{I_\omega\} = \sum_{m=-\infty}^{\infty} J_m(\alpha) [J_{m-p}(\alpha) + J_{m+p}(\alpha)]$$

¹Unlike [7]–[9], which use the small-signal admittance of the SIS junction, here we use the large-signal equations. We believe that the large-signal equations are more appropriate because the input signal is strong ($\alpha \sim 1$).

$$\times \text{Im} \{ I_{\text{R}}(V_{\text{b}} + mV_{\text{ph}}) \} \quad (6a)$$

$$\text{Im} \{ I_{\omega} \} = \sum_{m=-\infty}^{\infty} J_m(\alpha) [J_{m-p}(\alpha) - J_{m+p}(\alpha)] \times \text{Re} \{ I_{\text{R}}(V_{\text{b}} + mV_{\text{ph}}) \} \quad (6b)$$

where p is the harmonic number ($p=1$ for the fundamental frequency), J_m is the m^{th} order Bessel function of the first kind, $\alpha=|V_{\omega}|/V_{\text{ph}}$ is the normalized AC voltage (hereafter referred to as the junction drive level), $V_{\text{ph}}=\hbar\omega/e$ is the equivalent photon voltage, e is the charge of an electron, $\hbar=h/2\pi$ is the reduced Planck constant, I_{R} is the response function of the SIS junction and V_{b} is the DC bias voltage. The response function is defined as:

$$I_{\text{R}}(V_{\text{b}}) \equiv I_{\text{kk}}^0(V_{\text{b}}) + j I_{\text{dc}}^0(V_{\text{b}}) \quad (7)$$

where I_{dc}^0 is the DC tunneling current (with no AC signals present) and I_{kk}^0 is the Kramers-Kronig transform of I_{dc}^0 :

$$I_{\text{kk}}^0(V_{\text{b}}) = \frac{1}{\pi} \mathcal{P} \int_{-\infty}^{\infty} \frac{I_{\text{dc}}^0(V_{\text{b}}') - V_{\text{b}}'/R_{\text{n}}}{V_{\text{b}}' - V_{\text{b}}} dV_{\text{b}}'. \quad (8)$$

Here, \mathcal{P} represents the Cauchy principal value integral.

To simplify this model, the series components can be combined into a net impedance term Z and the shunt components can be combined into a net admittance term Y :

$$Z = W^{-1} \cdot (j\omega L_{\text{s}} + Z_{\text{sw}} + Z_{\text{sg}}) \quad (9a)$$

$$Y = W \cdot (j\omega C_{\text{s}} + Y_{\text{j}}). \quad (9b)$$

We can then calculate the propagation constant γ and the characteristic impedance Z_0 of the transmission line:

$$\gamma = \sqrt{Z \cdot Y} \quad (10a)$$

$$Z_0 = \sqrt{Z/Y}. \quad (10b)$$

If the DSJ is an open-circuit stub, such as the DSJ from [7]–[9], the input impedance can be calculated from:

$$Z_{\text{in}} = Z_0 \cdot \coth(\gamma L). \quad (11)$$

The current generated at the second harmonic I'_{ω} is then calculated from Eqn. 6 with $p=2$. (The third and fourth harmonics can be calculated in a similar manner with $p=3$ and $p=4$, respectively.) Finally, the output power from the DSM is:

$$P'_{\text{out}} = \frac{1}{2} |I'_{\omega}|^2 \cdot \text{Re}(Z_{\text{in}}). \quad (12)$$

A. Simulated Results

A simple DSJ model was generated for the purposes of this sub-section to illustrate the limitations of the quasi-nonlinear transmission line model. This DSJ has a width of 1 μm , a length of 20 μm and it was treated as an open-circuit stub. The other properties of the DSJ are listed in Table I, including the properties of the niobium layers and the DC electrical properties. For the DC current–voltage relationship (i.e., the DC I–V curve), we used a polynomial model [16]:

$$I_{\text{dc}}^0(V_{\text{b}}) = \frac{(V_{\text{b}}/V_{\text{gap}})^{2x+1}}{1 + (V_{\text{b}}/V_{\text{gap}})^{2x}} \cdot \frac{V_{\text{gap}}}{R_{\text{n}}} \quad (13)$$

Table I
PROPERTIES OF THE DSJ[†].

Property	Variable	Value	Unit
DSJ length	L	20	μm
DSJ width	W	1	μm
Wiring layer thickness	d_{w}	450	nm
Insulation barrier thickness	d_{i}	~ 1	nm
Ground layer thickness	d_{g}	250	nm
London penetration depth	λ_{L}	85	nm
Gap voltage	V_{gap}	2.88	mV
Normal-state resistance	R_{n}	1.59	Ω

[†] These properties match the DSM device from [7]–[9].

where V_{gap} is the gap voltage, R_{n} is the normal-state resistance and the value x controls the sharpness of the transition (set to $x=50$ for this example).

We simulated this DSJ using the quasi-nonlinear model (Eqns. 1–12) and the results are shown in Fig. 2. The top plot shows the propagation constant $\gamma=\alpha_{\gamma}+j\beta_{\gamma}$ multiplied by the length L of the DSJ, which is the one-way propagation through the DSJ. (Note that the attenuation constant α_{γ} has a subscript to differentiate it from the junction drive level α .) In the bottom plot, the input impedance Z_{in} is plotted along with the characteristic impedance Z_0 . The real component of the input impedance peaks whenever $\beta_{\gamma} \cdot L \approx n\pi$ for $n=1, 2, 3, \dots$. In Fig. 2, this occurs at 179.0 GHz, 351.3 GHz, 509.8 GHz and 644.9 GHz. There should also be a peak near 757.5 GHz, but above the gap frequency (~ 670 GHz), the attenuation is so high that the reflections from the open-circuit end are insignificant and so the input impedance approaches the value of the characteristic impedance. (To create a DSM that operates above 670 GHz, it would likely be necessary to use a material with a higher gap frequency, such as niobium-titanium-nitride.)

So far, this quasi-nonlinear model has assumed that the junction drive level is constant across the entire DSJ. However, attenuation and reflections from the open-circuit end would normally cause the drive level to change with position, as shown in Fig. 3a. This is an issue because different drive levels should then cause the tunneling admittance Y_{j} , the propagation constant γ and the characteristic impedance Z_0 to change with position as well, especially for bias voltages close to V_{gap} where the junction's admittance is very sensitive to α . For example, in Fig. 3b, the one-way attenuation is 8.3 dB at a drive level of $\alpha=2$, but this quickly rises to 19.4 dB at $\alpha=0.5$. The phase constant and characteristic impedance also change significantly between $\alpha \sim 0.5$ and $\alpha \sim 2$, but the quasi-nonlinear model is unable to simulate how Y_{j} , γ and Z_0 change with position along the DSJ. For that ability, we require a fully nonlinear transmission line model.

III. NONLINEAR DSJ TRANSMISSION LINE MODEL

The fully nonlinear DSJ transmission line model is presented in Fig. 4, with the model for the fundamental frequency in Fig. 4a and the model for the second harmonic in Fig. 4b. The DSJ is now divided into N segments where

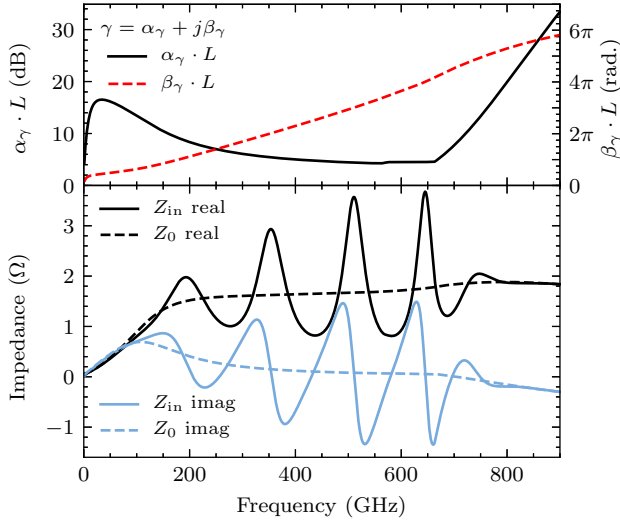


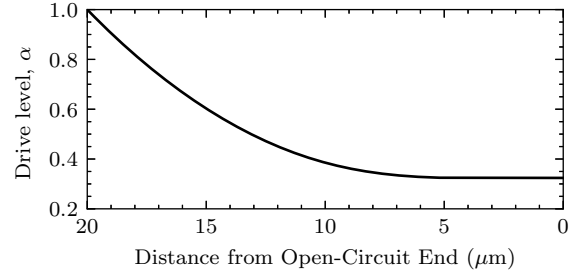
Figure 2. Simulated electrical properties from the quasi-nonlinear DSJ model. The top plot shows the one-way propagation, $\gamma \cdot L = (\alpha_\gamma + j\beta_\gamma) \cdot L$, and the bottom plot shows the input impedance Z_{in} and characteristic impedance Z_0 . For this simulation, the drive level was set to $\alpha=1$ and the bias voltage was set to $V_b = V_{gap} - V_{ph}/2$, which is the middle of the first photon step. The other properties of the DSJ are listed in Table I.

the segment length $\Delta x = L/N$ is set such that the drive level can be assumed to be constant over each unit length, similar to the analysis of distributed SIS mixers [17], [18]. (Using Fig. 3a as an example, if $\Delta x = L/40$, the maximum error on α is always less than 5%.) Unlike the quasi-nonlinear model, this new model allows Y_j , the propagation constant and the characteristic impedance to change with position, depending on the magnitude of the AC voltage at that position. Furthermore, it includes the transmission line characteristics of the second harmonic, which were not included in the quasi-nonlinear model from Sec. II.

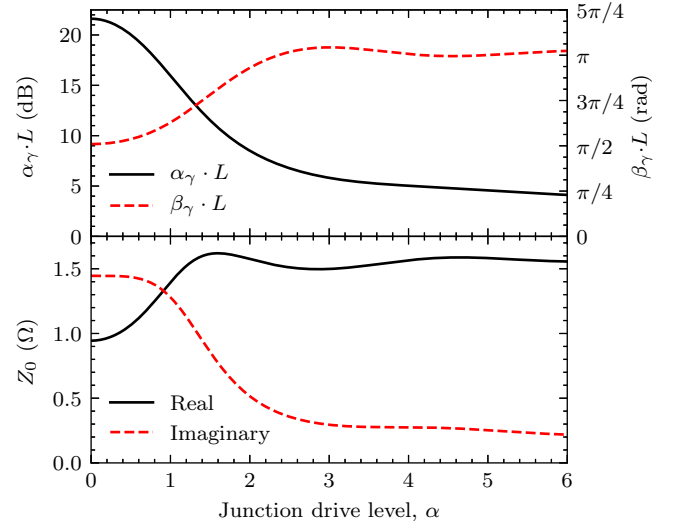
The circuit shown on the left-hand side of Fig. 4a represents the circuit within which the DSJ is embedded. If the embedding circuit is entirely linear, it can be reduced to a Thévenin equivalent circuit with voltage V_{emb} and impedance Z_{emb} . At the second harmonic (Fig. 4b), there is no input power, so the embedding circuit is only represented by a load impedance Z'_L . (We denote the properties of the second harmonic using a superscript '.)

The transmission line model shown in Fig. 4c is then used to cascade the voltages and currents through the segments of Figs. 4a and 4b. This model is similar to the previous quasi-nonlinear transmission line model (Fig. 1b), except that the tunneling current is now able to change with position and the magnitude of the AC voltage. The tunneling current is also now represented by a voltage-dependent current source, instead of an admittance, which is necessary in order to simulate the signal produced at the second harmonic².

²As seen in Eqn. 6, the AC tunneling current is a function of the DC bias voltage V_b and the AC voltages V_n and V'_n . If power is dissipated along the DSJ (e.g., at the fundamental frequency), we can convert I_ω to an admittance value, as we did in Eqn. 5. If power is generated (e.g., at the second harmonic), I'_ω should be modeled as a voltage-dependent current source (Fig. 4c). Here we decided to use voltage-dependent current sources for both harmonics, as given by Eqn. 6.



(a)



(b)

Figure 3. Investigating the limitations of the quasi-nonlinear DSJ model. For (a), we calculated γ and Z_0 assuming $\alpha=1$ (Eqns. 1–10), and then we used these values to calculate V_ω and α versus position. As we can see, $\alpha \neq 1$. In (b), the electrical properties are plotted at different drive levels. For both plots, the bias voltage was set to $V_b = V_{gap}$ and the frequency was set to $f = 179.0$ GHz (the first peak in Fig. 2). Note that in (a), we would normally expect to see voltage maximums at both ends of the $\sim \lambda/2$ open-circuit stub. However, due to the high attenuation seen in (b), we do not see this behavior since the reflections are too weak.

Using the transmission line model from Fig. 4c, the voltages and currents cascade as:

$$\begin{bmatrix} V_{n+1} \\ I_{n+1} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1} \begin{bmatrix} V_n \\ I_n \end{bmatrix} - \begin{bmatrix} 0 \\ I_{\omega;n}(V_n, V'_n) \end{bmatrix} \quad (14)$$

where n is the position index from Fig. 4a, the $ABCD$ -matrix represents the linear components in Fig. 4c, and $I_{\omega;n}$ is the AC tunneling current in segment n resulting from the voltages V_n and V'_n . Note that to calculate $I_{\omega;n}$ using Eqn. 6, we have to replace I_R by the effective response function of a single segment of the DSJ model:

$$I_R^s(V_b) = \frac{I_R(V_b)}{N} = \frac{I_{kk}^0(V_b) + j I_{dc}^0(V_b)}{N}. \quad (15)$$

In other words, since I_R is proportional to I_{dc}^0 , which is itself proportional to the area of the junction, we have to divide I_R by N to solve for the single-segment response function I_R^s .

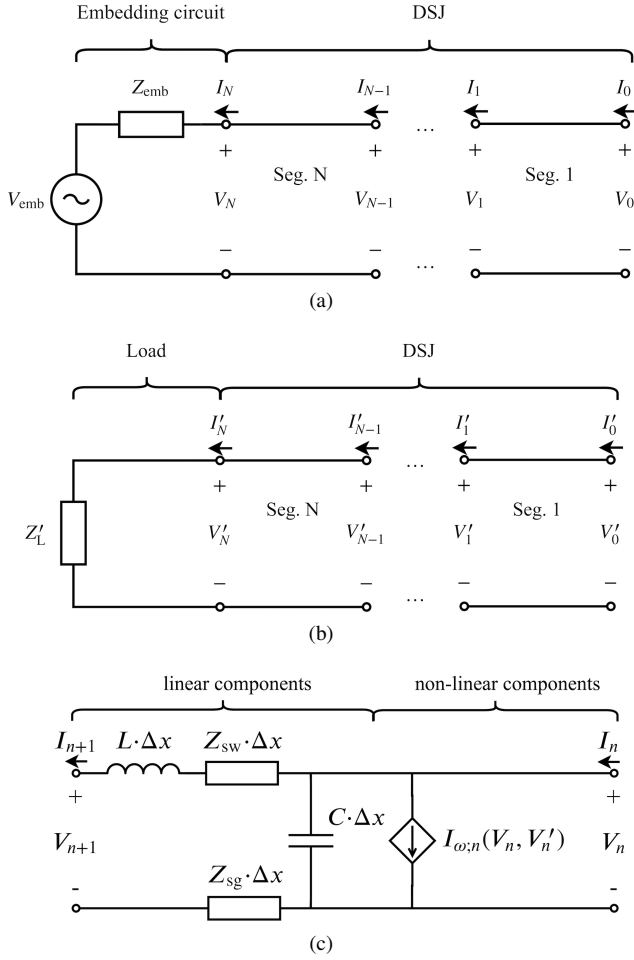


Figure 4. Nonlinear DSJ transmission line models for the fundamental frequency (a) and the second harmonic (b). In both models, the transmission line is divided into N segments. Each segment in (a) uses the model shown in (c) to cascade the voltages and currents. There is an equivalent of (c) for the second harmonic, except that the first harmonic values are replaced with their second harmonic analogues (i.e., $V_n \rightarrow V'_n$, $I_n \rightarrow I'_n$, $I_{\omega;n} \rightarrow I'_{\omega;n}$, etc.).

In Eqn. 14, the complex coefficients of the $ABCD$ -matrix are calculated by [11]:

$$A = \cosh(\gamma \cdot \Delta x) \quad (16a)$$

$$B = \sinh(\gamma \cdot \Delta x) \cdot Z_0 \quad (16b)$$

$$C = \sinh(\gamma \cdot \Delta x) / Z_0 \quad (16c)$$

$$D = \cosh(\gamma \cdot \Delta x). \quad (16d)$$

The propagation constant γ and characteristic impedance Z_0 are again calculated by Eqn. 10, except that the tunneling current is no longer included in the admittance term Y (Eqn. 9b). Instead, the admittance term is simply:

$$Y = W \cdot j\omega C_s. \quad (17)$$

For Eqns. 14–17, there is also an identical set of equations for the second harmonic, except that the first harmonic values are replaced with their second harmonic analogues, i.e., $V_n \rightarrow V'_n$, $I_n \rightarrow I'_n$, $I_{\omega;n} \rightarrow I'_{\omega;n}$, $\gamma \rightarrow \gamma'$, and $Z_0 \rightarrow Z'_0$.

With the nonlinear DSJ model in place, it is then necessary to solve for the voltages V_0 and V'_0 that satisfy the embedding circuits for both harmonics simultaneously. (Recall that V_0

represents the voltage at position index 0 and not the DC bias voltage, which is represented by V_b .) To accomplish this, we began by assuming initial values for V_0 and V'_0 . (I_0 and I'_0 are equal to zero at the open-circuit end of the DSJ.) We found that initial values of $V_0 = V_{emb}$ and $V'_0 = V_{emb} \div 10$ were typically adequate. These values were then cascaded to the opposite end of the DSJ using Eqn. 14. For the first and second harmonics, respectively, the resulting voltage errors at position index N are:

$$\Delta = I_N \cdot Z_{emb} - V_N - V_{emb} \quad (18a)$$

$$\Delta' = I'_N \cdot Z'_L - V'_N. \quad (18b)$$

The goal is then to find V_0 and V'_0 such that Δ and Δ' are equal to zero. This is challenging because the equations are highly nonlinear functions of V_0 and V'_0 , and the variables are complex values with both real and imaginary components.

To find a solution to Eqn. 18, we used the Newton-Raphson method, which is an iterative root-finding algorithm, similar to the harmonic balance procedure presented in [19]. Through each iteration, the estimated AC voltage is updated by:

$$\mathbf{V}_0^{k+1} = \mathbf{V}_0^k - [J(\mathbf{V}_0^k)]^{-1} \cdot \Delta(\mathbf{V}_0^k) \quad (19)$$

where k represents the iteration number and the bold face notation represents column vectors:

$$\mathbf{V}_0 = \begin{bmatrix} \text{Re } V_0 \\ \text{Im } V_0 \\ \text{Re } V'_0 \\ \text{Im } V'_0 \end{bmatrix}; \quad \Delta = \begin{bmatrix} \text{Re } \Delta \\ \text{Im } \Delta \\ \text{Re } \Delta' \\ \text{Im } \Delta' \end{bmatrix}. \quad (20)$$

$J(\mathbf{V}_0)$ is then the Jacobian of Eqn. 18, which represents the sensitivity of the error Δ to small perturbations in \mathbf{V}_0 . For a DSJ transmission line with two harmonics, the Jacobian will be a 4×4 matrix with values:

$$J(\mathbf{V}_0) = \begin{bmatrix} \frac{\partial \text{Re } \Delta}{\partial \text{Re } V_0} & \frac{\partial \text{Re } \Delta}{\partial \text{Im } V_0} & \frac{\partial \text{Re } \Delta}{\partial \text{Re } V'_0} & \frac{\partial \text{Re } \Delta}{\partial \text{Im } V'_0} \\ \frac{\partial \text{Im } \Delta}{\partial \text{Re } V_0} & \frac{\partial \text{Im } \Delta}{\partial \text{Im } V_0} & \frac{\partial \text{Im } \Delta}{\partial \text{Re } V'_0} & \frac{\partial \text{Im } \Delta}{\partial \text{Im } V'_0} \\ \frac{\partial \text{Re } \Delta'}{\partial \text{Re } V_0} & \frac{\partial \text{Re } \Delta'}{\partial \text{Im } V_0} & \frac{\partial \text{Re } \Delta'}{\partial \text{Re } V'_0} & \frac{\partial \text{Re } \Delta'}{\partial \text{Im } V'_0} \\ \frac{\partial \text{Im } \Delta'}{\partial \text{Re } V_0} & \frac{\partial \text{Im } \Delta'}{\partial \text{Im } V_0} & \frac{\partial \text{Im } \Delta'}{\partial \text{Re } V'_0} & \frac{\partial \text{Im } \Delta'}{\partial \text{Im } V'_0} \end{bmatrix}. \quad (21)$$

In our experience, this method typically requires 5–15 iterations to converge on a solution, depending on the embedding circuit, the response function and the bias voltage.

Once the simulation is complete, the power delivered to the load at the second harmonic is calculated by:

$$P'_{\text{out}} = \frac{|V'_N|^2}{2 \cdot \text{Re} \{Z'_L\}}. \quad (22)$$

This value is then used to calculate the efficiency of the DSM:

$$\eta = \frac{P'_{\text{out}}}{P_{\text{emb}}} \quad (23)$$

where P_{emb} is the available power from the embedding circuit:

$$P_{\text{emb}} = \frac{|V_{\text{emb}}|^2}{8 \cdot \text{Re} \{Z_{\text{emb}}\}}. \quad (24)$$

The goal of any DSM device should be to maximize the efficiency η and the output power P'_{out} .

IV. COMPARING THE NEW NONLINEAR DSJ MODEL TO EXPERIMENTAL DATA

We recently reported a new DSM device that uses two $1\ \mu\text{m} \times 20\ \mu\text{m}$ DSJs mounted in parallel, with each DSJ added to the planar circuit as an open-circuit stub [7]–[9]. Bandpass filters were placed on either side of the DSJs to set the direction of the output signal and to prevent leakage between the input and output waveguides. The electrical properties and the geometry of the DSJs are listed in Table I and a diagram of the planar circuit can be found in [7].

When we tested this device, the input signal was injected at 93 GHz and this produced an output signal at 186 GHz, which is double the input frequency. During the experiment, we recorded the DC tunneling current, with and without the input signal applied, and we measured the output power using a separate SIS mixer chip. We then de-embedded the measured power by estimating the loss between the DSM and the SIS mixer. In addition to the loss estimated in [7]–[9], in this paper we have also included 1 dB of loss from the waveguide probes (due to a scaling error in the experimental device), 1.4 dB of loss due to the conversion gain of the SIS mixer [20] and 3.3 dB of loss due to the impedance mismatch between the SIS device and the IF measurement circuit.

Previously, Rashid *et al.* [7]–[9] compared the experimental data from this DSM device to the quasi-nonlinear model from Sec. II. In this section, we now compare the experimental data to the new fully nonlinear model from Sec. III. First, we used the experimental DC currents to estimate the properties of the embedding circuit (Sec. IV-A), and then we simulated the AC signal at the fundamental frequency (Sec. IV-B) and the output power at the second harmonic (Sec. IV-C).

For the simulations in this section, we used the QMix software package³ to calculate the quasiparticle tunneling currents [21]–[23], instead of Eqn. 6. QMix uses multi-tone spectral domain analysis [24]–[26], which makes the software ideal for simulating higher-order harmonics, such as those present within DSJ transmission lines. It also has built-in utilities for importing and filtering the experimental DC I–V curve, calculating the Kramers-Kronig transform and interpolating the response function. Furthermore, the QMix code has extensive unit tests, which reduces the likelihood of errors in our simulations. In brief, we could have used Eqn. 6 alone, but we chose to use QMix since it is a powerful software package that facilitates working with experimental data.

A. Recovering the Embedding Circuit

To begin, we recovered the properties of the embedding circuit by analyzing the experimental DC tunneling currents, similar to what is normally done with SIS mixers [27], [28]. We started by estimating a voltage at position index 0 and cascading this value across the DSJ to find all of the voltages

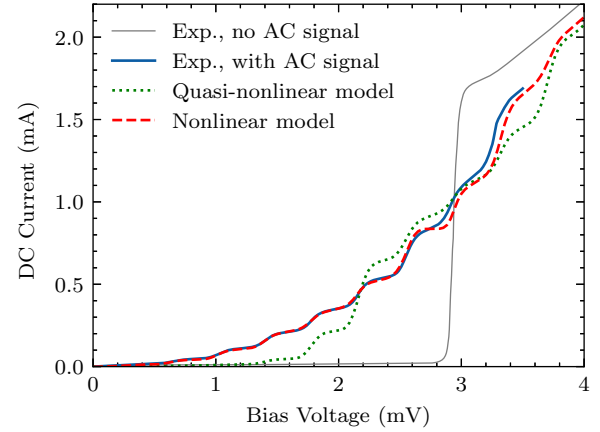


Figure 5. DC tunneling current from the nonlinear model compared to experimental data. For the simulation, the embedding voltage was $V_{emb}=2.95\ \text{mV}$ and the embedding impedance was $Z_{emb}=1.20+j1.36\ \Omega$. The frequency of the fundamental harmonic was 93 GHz. The DC tunneling current from the quasi-nonlinear model is also included (assuming $\alpha=3$).

V_n and currents I_n . Using these values, we then calculated the DC tunneling current in each segment n [15]:

$$I_{dc;n}(V_b) = \sum_{m=-\infty}^{\infty} J_m^2(\alpha_n) \cdot \text{Im} \{I_R^s(V_b)\} \quad (25)$$

where $\alpha_n=|V_n|/V_{ph}$ is the drive level of segment n , and $I_R^s(V_b)$ is the single-segment response function (Eqn. 15). The total DC tunneling current through the DSJ is then:

$$I_{dc}(V_b) = \sum_{n=0}^{N-1} I_{dc;n}(V_b). \quad (26)$$

By comparing this value to the experimental DC current, we revised our V_0 estimate through several iterations to recover V_n and I_n at each bias voltage. The embedding circuit was then estimated from the V_N and I_N values using a least squares fitting [28]. With SIS mixers, this technique is normally performed over the first photon step, but here we used the first 5 photon steps to improve the accuracy of the estimation, i.e., from $V_b \sim 1\ \text{mV}$ to $V_b \sim 2.8\ \text{mV}$. For this data set, the estimated embedding voltage and impedance were $V_{emb}=2.95\ \text{mV}$ and $Z_{emb}=1.20+j1.36\ \Omega$, respectively, giving the embedding circuit an estimated available power of $P_{emb}=907\ \text{nW}$.

Using this embedding circuit, we then simulated the DC tunneling current, as shown in Fig. 5. Below the gap voltage, the simulated current is very close to the experimental value with an RMS error of $0.7\ \mu\text{A}$ between $0\ \text{mV}$ and $2.8\ \text{mV}$. Above $\sim 2.6\ \text{mV}$, heating effects likely lower the effective gap voltage, resulting in a leftward shift in the experimental DC tunneling current. For comparison, we have also included the quasi-nonlinear model from Sec. II in Fig. 5. As we can see, the new nonlinear model has a much better fit to the experimental data, suggesting that it provides a more accurate description of the DSJ's behavior.

³Online: <https://github.com/garrettj403/QMix>

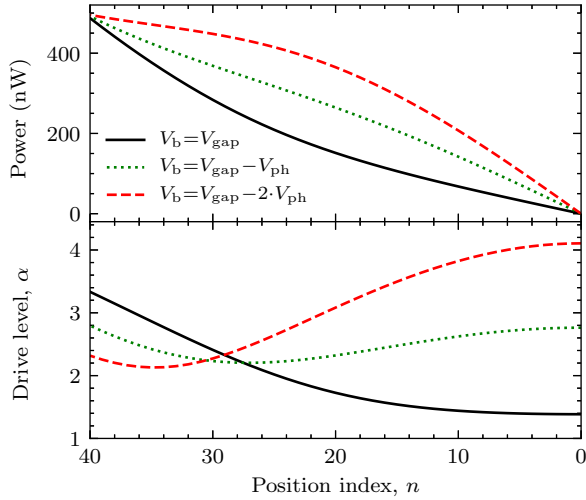


Figure 6. Simulated AC power (top) and drive level (bottom) at the fundamental frequency (93 GHz). The position index n corresponds to the indices shown in Fig. 4. The total number of segments was $N=40$.

B. AC Properties at the Fundamental Frequency

Next, we simulated the AC signal at the fundamental frequency. In Fig. 6, the drive level and AC power are plotted as a function of position. The AC power at position index n was calculated by:

$$P_n = \frac{1}{2} \text{Re} \{ V_n \cdot I_n^* \} \quad (27)$$

where I_n^* represents the complex conjugate of I_n . As expected, the AC power decreases monotonically with distance along the DSJ. In contrast, the drive level both increases and decreases as a function of position and bias voltage. Across all positions and voltages, the maximum simulated drive level is $\alpha=6.1$ at $(n, V_b)=(0, 0.0 \text{ mV})$ and the minimum is $\alpha=0.1$ at $(n, V_b)=(37, 0.1 \text{ mV})$. Recall that the quasi-nonlinear model did not allow Y_J to change with α or position, which limited the accuracy of the simulations.

C. Output Power at the Second Harmonic

Finally, we simulated the output power from the DSM device at the second harmonic. In Fig. 7, the simulated power is compared to the experimental data and the quasi-nonlinear model from Sec. II. For the nonlinear DSJ simulation, we used the embedding circuit from Sec. IV-A, but the precise value of the load impedance Z'_L at the second harmonic was unknown. In our previous work [7], we estimated that the value of Z'_L should be approximately 2.3Ω ; therefore, for our simulation, we swept the magnitude of Z'_L from 1Ω to 4Ω and the phase from -90° to $+90^\circ$. From these values, the simulated output power with $Z'_L=1.6-j1.6 \Omega$ was found to provide the best match to the experimental data. This value is equivalent to $Z'_L=2.3\angle 45^\circ \Omega$, which is consistent with our previous estimation. It could be possible to improve the fit to the experimental data by using more accurate values for Z_{emb} and Z'_L , but it is challenging to recover these impedances from the experimental data.

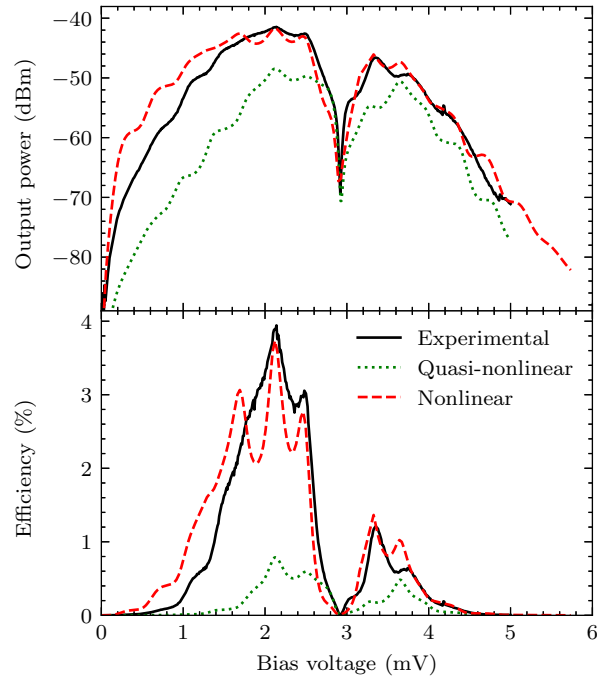


Figure 7. Output power (top) and conversion efficiency (bottom) of the DSM device. For the nonlinear model, we used the embedding circuit from Sec. IV-A and a load impedance of $Z'_L=1.6-j1.6 \Omega$. We have also included the results from the quasi-nonlinear model for comparison.

Despite the uncertainty in Z_{emb} and Z'_L , the agreement between the nonlinear DSJ model and the experimental results is very good, with an excellent fit above $\sim 1.6 \text{ mV}$. The new model also provides a much better fit than the quasi-nonlinear model, which estimates a significantly lower output power (Fig. 7). Overall, these results demonstrate that the new nonlinear model is able to accurately simulate the experimental behavior of the DSJ, suggesting that it can be used to design new DSM devices and optimize their performance.

V. OPTIMIZING A NEW DSM DEVICE

In the nonlinear DSJ model, there are five degrees of freedom, not including the properties of the DSJ itself. These parameters are the bias voltage V_b , the embedding voltage V_{emb} , the embedding impedance Z_{emb} , the load impedance Z'_L and the frequency of the fundamental tone f . The impedance values can also split into their real and imaginary components, which would result in two additional degrees of freedom. Optimizing all of these values is computationally expensive; however, we made an initial attempt by constraining several of the free parameters.

To begin, we set the frequency to 100 GHz and the bias voltage to $V_b=V_{\text{gap}}-2 \cdot V_{\text{ph}}$, which is the location of the maximum output power in the experimental data (Fig. 7). We then simulated the DSJ assuming a strong input signal ($|V_n| \sim 3 \cdot V_{\text{ph}}$) and found that the length of the DSJ is equal to $\lambda/2$ when $L=35 \mu\text{m}$, where λ is the guided wavelength. For this length, the input impedance of the DSJ is $Z_{\text{in}}=7.56+j0.59 \Omega$. By taking the complex conjugate of this value (to maximize the power delivered to the DSJ), we estimated an optimal embed-

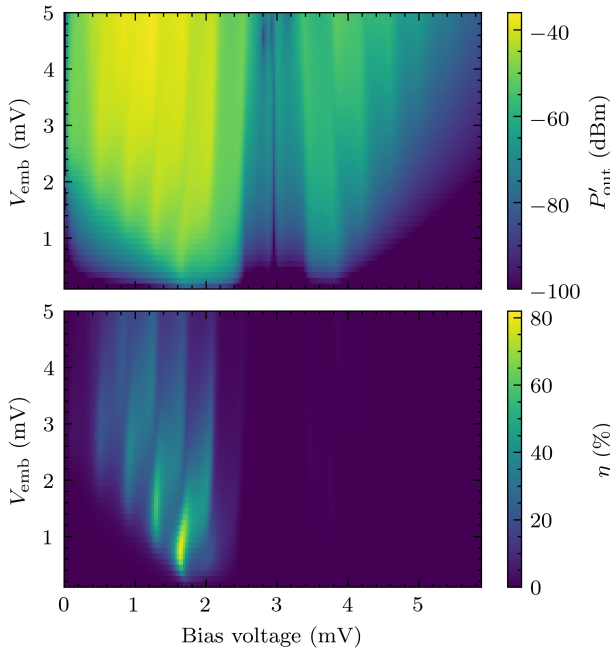


Figure 8. Simulated output power (top) and efficiency (bottom) of the optimized DSM device. For this simulation, the frequency was 100 GHz, the length was 35 μm , the embedding voltage was $Z_{emb}=7.56-j0.59 \Omega$ and the load impedance was $Z'_L=5+j20 \Omega$.

ding impedance of $Z_{emb}=7.56-j0.59 \Omega$. Finally, we swept the real and imaginary components of the load impedance Z'_L and simulated the output power from each value. We found that inductive Z'_L values provide the highest output powers.

As seen in Fig. 8, with $Z'_L=5+j20 \Omega$, the optimized DSJ simulation provides an output power of -37 dBm at $(V_b, V_{emb})=(1.24, 5.0)$ mV and an efficiency of 80% at $(V_b, V_{emb})=(1.62, 0.7)$ mV. Since SIS junctions require approximately -40 dBm of LO power, this power level would be enough to pump an SIS mixer (if the signal were injected into the mixer through an RF hybrid). The maximum conversion efficiency shown in Fig. 8 is lower than the value predicted by the quasi-nonlinear DSJ model ($\eta \sim 95\%$ [7]), but it is much higher than the efficiency of modern Schottky diode frequency multipliers⁴ ($\eta \sim 30\%$ at 200 GHz [29]). We suspect that the efficiency can be extended beyond 80% by further optimizing the DSJ model. For example, in future work we could simulate a wider range of parameters or use a better optimization algorithm. We could also use a DSJ with a higher current density, which would allow us to achieve a higher input impedance and likely a better match to the embedding circuit.

The proposed DSJ is 75% larger than the DSJ presented by Rashid *et al.* [7]–[9]. Based on our experience, it should be feasible to fabricate a junction of this size. The highly inductive embedding impedance at the second harmonic could be more difficult; however, it should also be attainable since it is only required over a limited frequency range.

⁴Recall that the motivation for DSM devices is high conversion efficiency at frequencies above ~ 100 GHz, mostly for LO chains in astronomical receivers. Schottky diodes still offer many advantages including the ability to operate at room temperature with much higher signal powers.

VI. CONCLUSION

In this paper, we presented a new nonlinear transmission line model for simulating distributed SIS frequency multipliers. Unlike previous models, this new model captures how the tunneling current changes with position and AC power, allowing for nonlinear propagation parameters and more accurate simulations. We compared the new nonlinear model to experimental data and found very good agreement. Both the simulated DC tunneling current and the output power at the second harmonic closely matched the experimental data; although, there was some uncertainty in the experimental values. Based on this success, we simulated the optimal embedding circuit to maximize the conversion efficiency and output power at the second-harmonic. According to these simulations, an optimized SIS frequency doubler should be able to provide an efficiency of 80% and an output power of -37 dBm, which is enough to drive an SIS mixer. We suspect that the performance could be further optimized in the future, allowing for SIS frequency multipliers with even higher conversion efficiencies. Overall, this work will help to develop efficient local-oscillator sources and support new astronomical receivers at millimeter and submillimeter wavelengths, including SIS receivers that operate above 1 THz and large-scale focal plane arrays. In future work, we hope to fabricate the optimized DSM device and continue to validate the nonlinear DSJ model with additional experimental data.

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