SIMULATION OF THE PERFORMANCE OF A 5-JUNCTION ARRAY FOR 780-950GHz

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Abstract: The performance of a five-junction (Nb/AlOx/Nb) array is characterized in the frequency range of 780-950GHz for different wiring and ground layers of the thin-film microstrip lines of the junction tuning inductance and the associated impedance transformer. Three kinds of thin films (i.e., Nb, Al, and NbTiN) are taken for this investigation. The individual SIS junctions of the five-junction array have an area of $1\mu m^2$ and a critical current density of $10kA/cm^2$. The performance of parallel-connected twin junctions, which have the same junction parameters as those of the five-junction array, is also studied for comparison.

I. Introduction

As is well known, it is effective to enlarge the bandwidth of SIS mixers by increasing the critical current density of the SIS junction or adopting broadband mixing circuitry. However, the higher the junction's critical current density J_c is, the lower the junction quality (i.e., smaller $R_{sub}(2mV)/R_n$) becomes. SIS junctions of a small quality factor usually have low mixing conversion gain and high noise temperature, especially at submillimeter wavelengths. Hence it is of particular interest to develop submm SIS mixers with low-J_c junctions (say less than $10kA/cm^2$ for Nb ones) incorporating with broadband junction tuning circuitry. Distributed junction arrays have demonstrated broadband performance at frequencies below the gap frequency (~680GHz) of Nb SIS junctions [1-2]. It still remains unclear, however, whether they can perform well beyond the junction's gap frequency as far as the thin-film losses of the junction tuning inductance (longer than lumped cases) and the associated impedance transformer (usually with larger impedance transforming ratio [3]) are concerned.

To develop a 780-950GHz SIS mixer, we investigated the performance of a five-junction (Nb/AlOx/Nb) array and compare it with that of parallel-connected twin junctions. Different superconducting and normal-metal thin films such as Nb, Al, and NbTiN were adopted as the wiring and ground layers of the thin-film microstrip lines of the junction tuning inductance and the associated impedance transformer. We also examined the effects of the junction quality and film thickness on the mixing performance of the two investigated tuning circuits.

II. Simulation Model

For both the five-junction array and the parallel-connected twin junctions, the individual SIS junctions were assumed to have an area of $1\mu m^2$ and a critical current density of $10kA/cm^2$. Note that the junction's specific capacitance and product of I_cR_n were taken as $90fF/\mu m^2$ and 1.95mV, respectively. We had two junction I-V curves of different quality factors, which were digitized from the real I-V curves of two SIS junctions (refer to sisiv-1 and sisiv-2 in Fig. 1). An impedance transformer was included for the two cases to have good RF matching between the junction tuning circuit and a real mixer block for 780-950GHz (scaled from a 660-GHz one [4]), whose embedding impedance (normalized to 35ohm) was calculated by HFSS [5] (refer to Fig. 2).

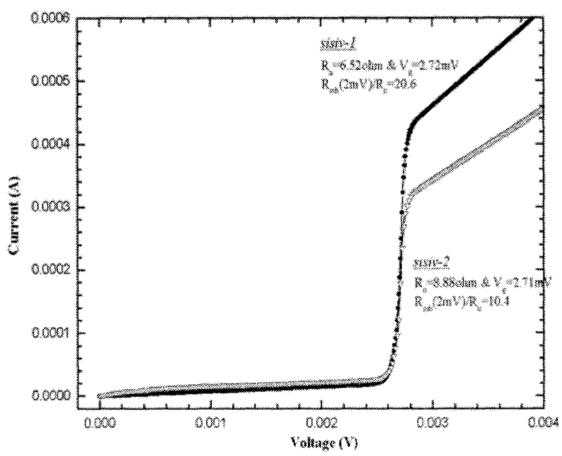

Fig. 1 Two digitized junction I-V curves (sisiv-1 and sisiv-2) used for simulation.

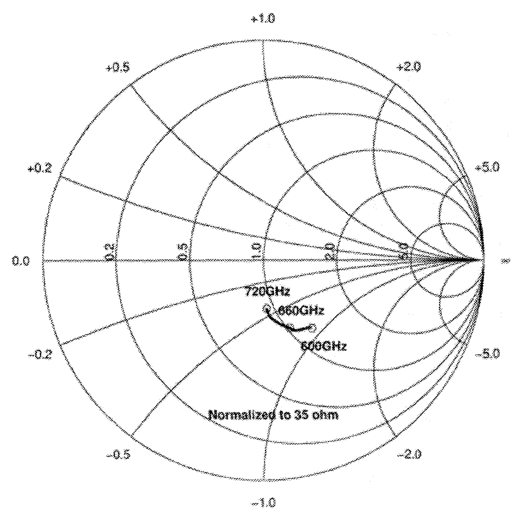

Fig. 2 Simulated embedding impedance for a 780-950GHz SIS mixer.

The mixing model of the five-junction array and parallel-connected twin junctions used here is almost the same as described in [1], except for the introduction of the loss effect of thin-film superconducting microstrip lines. At first, we calculated the local-oscillator (LO) voltage, including amplitude and phase, distribution among the individual SIS junctions, by assuming a fixed reduced LO voltage (α) for the last junction (according to the signal transmission direction). The equivalent conversion admittance matrix [Y] for the junction array was then obtained by combining the conversion admittance matrixes of the individual SIS junctions with the equivalent lumped impedance and admittance for the tuning microstrip line between two individual junctions. We had the equivalent noise correlation matrix [H] for the junction array by transforming the noise currents (thermal and shot, at different small-signal sidebands) of the individual junctions to the input port of the junction array and then having an equivalent short-circuited noise current at the input port for all the noise contributions. With the equivalent mixing model, it is straightforward to simulate the performance of the junction array by means of the quantum theory of mixing.

As introduced before, three kinds of thin films (i.e., Nb, Al, NbTiN) were selected as the wiring and ground layers of the thin-film microstrip lines of the junction tuning inductance and the associated impedance transformer. Nb and NbTiN thin films had an energy gap and normal-state conductivity of Δ=1.45mV & σ_n=1.4e7Ω^{-1}m^{-1} (@ 9.2K) and Δ=2.47mV & σ_n=1.0e6Ω^{-1}m^{-1} (@ 20K) [6-7] respectively, while Al films had a ratio of σ_n/l_e=2.55e15Ω^{-1}m^{-2} [8]. The surface impedance of Al films was calculated according to Reuter-Sondheimer equation (nonlocal anomalous skin effect) [9], while those of Nb and NbTiN films according to Mattis-Bardeen theory [10]. The dielectric of the microstrip lines for the tuning inductance and impedance transformer had three layers, i.e., $Al_2O_3/SiO_2/Nb_2O_5$, which have respective dielectric constants and thicknesses of 9/0.09μm, 4/0.27μm, and 29/0.10μm (based on the fabrication process of Nb SIS junctions at Nobeyama Radio Observatory, Japan).

Given the fact that the effect of the spreading inductance around the SIS junctions, which is comparable to the junction tuning inductance at submm wavelengths, is no longer negligible, we assumed a short section of microstrip line (lossless, but with the same width as the tuning inductance) before and after each individual SIS junction as an equivalent spreading inductance [11]. For the simulated cases (5μm-wide tuning inducatnce and 1μm-wide junction), the length was found to be 0.7μm in terms of the modeling results for the 660-GHz SIS mixer (1μm) [12].

III. Simulation Results

Assuming an IF noise temperature of 15K and an SIS I-V curve as sisiv-2 (R_n=8.88ohm, V_{gap}=2.71mV, and R_{sub}(2mV)/R_n=10.4), we firstly simulated the receiver noise temperatures (SSB) of the five-junction array and parallel-connected twin junctions for 780-950GHz. Here we investigated five instances of different ground-/wiring-layers for the thin-film microstrip lines of the junction tuning inductance and associated impedance transformer, which are Nb/Nb, Al/Al, NbTiN/NbTiN, NbTiN/Al, and Nb/Al, respectively. Notice that the Nb and Al films were assumed to be 0.6μm thick for the wiring layer and 0.2μm thick for the ground layer, while the NbTiN film 0.6μm thick for the wiring layer and 0.3μm thick for the ground layer. The calculated results are shown in Fig. 3a-b. It should be pointed out that for each instance, both the impedance transformer (width and length) and the tuning inductance (length only, of a fixed width of 5μm) were optimized for the lowest receiver noise temperature and the largest bandwidth (refer to Fig. 3), and the LO pumping level of the last junction was optimized at each frequency with all the individual SIS junctions dc-biased at a fixed voltage of 2mV.

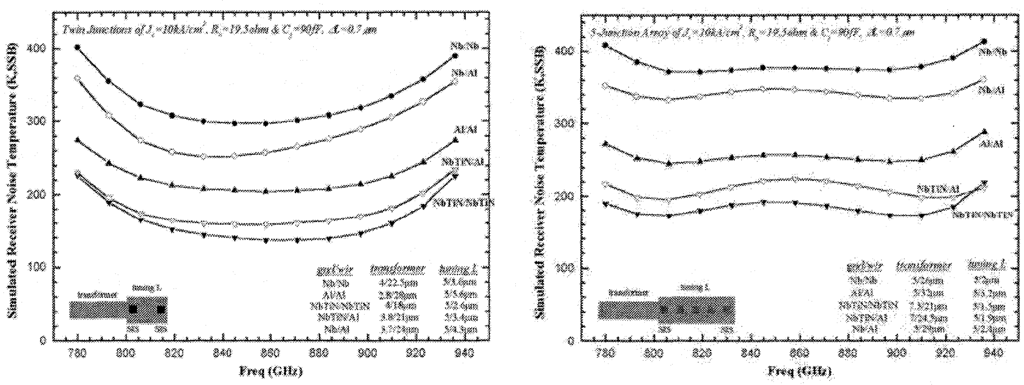

Fig. 3 Simulated receiver noise temperature as a function of frequency (with sisiv-2) for Nb, Al, and NbTiN tuning circuits, with a) for parallel-connected twin junctions (left) and b) for five-junction array (right).

We can see clearly from Fig. 3a-b that for all the simulated five instances, the five-junction array has a large bandwidth but a high receiver noise temperature in comparison to the parallel-connected twin junctions. The difference of the receiver noise temperature, however, becomes smaller for the instance with all NbTiN films, even for the instance just with a NbTiN film for the ground layer. Obviously, while having good bandwidth performance, distributed junction arrays still can have good noise performance beyond the junction's gap frequency if low-loss thin films (either superconducting or normal metallic) are adopted for the junction array's tuning microstrip line. It is also interesting to indicate that for both the five-junction array and the parallel-connected twin junctions, the instance of the Al/Al combination has much better noise performance than the Al/Nb one while the difference is not large between the NbTiN/Al and the NbTiN/NbTiN combination.

As the magnetic penetration depth of NbTiN superconducting films (~220nm) is much larger than that of Nb films (for all Nb junctions we used to have 200nm-thick ground layer), it is necessary to examine the effect of the thickness of the NbTiN ground layer on the mixing performance. Fig. 4a-b shows the simulated receiver noise temperature for the five-junction array and parallel-connected twin junctions for three different thicknesses of the NbTiN ground layer (i.e., 0.2, 0.3, and 0.4μm). Obviously, the frequency response of the receiver noise temperature does not change considerably when the thickness is larger than 0.3μm.

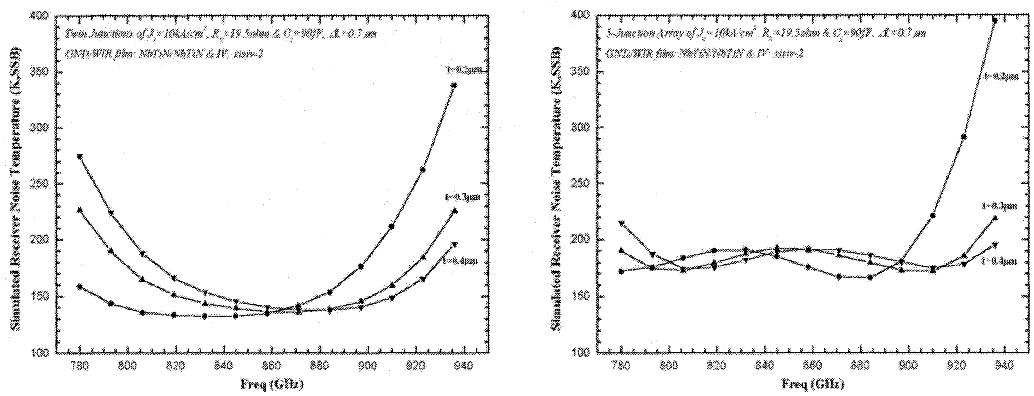

Fig. 4 Simulated receiver noise temperature as a function of frequency (with sisiv-2) for NbTiN tuning circuit of different ground-film thicknesses (0.2, 0.3 and 0.4μm), with a) for parallel-connected twin junctions (left) and b) for five-junction array (right).

By simulating the performance of the five-junction array and parallel-connected twin junctions with a new junction I-V curve of a larger quality factor (sisiv-1, also plotted in Fig. 1, R_n=6.52ohm, V_{gap}=2.72mV, and R_{sub}(2mV)/R_n=20.6), we tried to understand how the noise performance of distributed junction arrays changes with the junction quality. Three instances, i.e., Nb/Nb, Al/Al, and NbTiN/NbTiN combinations for the ground-/wiring-layer, were selected for this investigation. As demonstrated in Fig. 5a-b, the receiver noise temperature was improved significantly, especially for the instance of the Nb/Nb combination. It has been found that the improvement is due mainly to that of the mixer noise temperature as the mixer conversion gain varies less than 1dB.

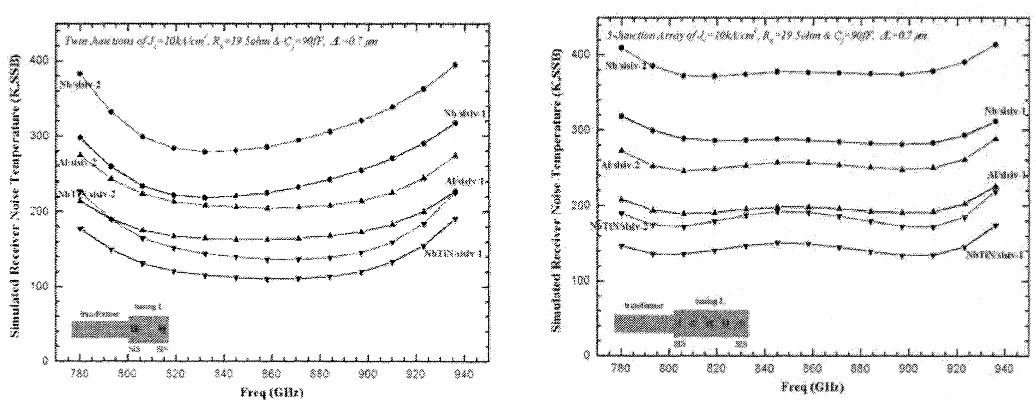

Fig. 5 Simulated receiver noise temperature as a function of frequency with different I-V curves (sisiv-1: solid & sisiv-2: dash) for Nb, Al, and NbTiN tuning circuits , with a) for parallel-connected twin junctions (left) and b) for five-junction array (right).

IV. Summary

The performances of a five-junction (Nb) array and parallel-connected twin junctions (Nb) have been thoroughly investigated in the frequency range of 780-950GHz for the Nb, Al, and NbTiN wiring and ground layers of the thin-film microstrip lines of the junction tuning inductance and the associated impedance transformer. It has been found that the five-junction array has a large bandwidth in general over the parallel-connected twin junctions and a comparable receiver noise temperature when employing NbTiN films. In addition, the receiver noise temperatures of the two junction tuning circuits with NbTiN films are less sensitive to the junction quality than with Nb films.

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