Development of a 600-720 GHz SIS Mixer for the SMART

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Abstract: The SMART (Sub-Mm-ARray-Taiwan) is an expansion project of SAO's SMA project. A 600-720 GHz SIS mixer for this project is under development. The SIS mixer is incorporated with a fixed-tuned waveguide mixer mount, which was originally designed by the receiver team at SAO, and a twin-junction (in parallel) tuning circuit. Individual Nb junctions have an area of 1.2x1.2μm^2 and a critical current density of 10kA/cm^2. Detailed simulation and experimental results are presented in this paper.

1. Introduction

The submillimeter-wave array (SMA) is a unique eight-element interferometer array, sited on Mauna Kea in Hawaii, being jointly developed by the Smithsonian Astrophysical Observatory (SAO) and the Academia Sinica Institute of Astronomy & Astrophysics (ASIAA) [1]. The array will cover a frequency range of 176-900 GHz, in which the 600-720 GHz band will be the first submillimeter band to operate. As it is well known, this frequency band is located just around the gap frequency of Nb SIS junctions. The performance of Nb SIS mixers is well close to $3h\nu/k$ below the junction's gap frequency, but can be further improved beyond that frequency. Developing good performance SIS mixers at submillimeter wavelengths is of particular interest for ground-based observational facilities because of large atmospheric attenuation.

2. SIS Mixer Design

Submillimeter-wave SIS mixers usually adopt SIS junctions in association with an integrated tuning circuit (an inductive thin-film superconducting microstrip line in general), which tunes out the junction's geometric capacitance. The surface resistance of superconducting films becomes considerable beyond the junction's gap frequency (~670 GHz for Nb junctions), due to Cooper-pair breaking by energetic photons. Hence it might be better to develop the 600-720 GHz SIS mixer using either junctions of a higher gap frequency [2] or Nb junctions incorporated with tuning films of smaller surface impedance (e.g., NbTiN/Al combination [3]), as far as the loss effect of superconducting films is concerned. All Nb junctions were indeed chosen for the first phase development, as the Nb-junction fabrication process is much mature in our labs. The mixer mount adopted for this development is the same as that by the receiver group at SAO [4].

Using all Nb junctions to develop a good performance SIS mixer for 600-720 GHz, we need to understand two points. One is how large the effect of the Nb thin-film loss on the mixer performance is, and the other is if the thin-film loss has similar impact for different junction tuning circuits.

2a. Loss effect for Nb thin-film microstrips

Let us consider a superconducting microstrip line of conductor width w and insulation-layer thickness h. The distributed parameters of the microstrip line, surface resistance R, inductance L, and capacitance C per unit length are given by

$$R = \frac{2}{Kw}\mathrm{Re}(Z_s) \qquad (\Omega / length) \tag{1}$$

$$L = \frac{\mu_0 h}{Kw} + \frac{2}{Kw}\mathrm{Im}(Z_s)/\, j\omega \qquad (H / length) \tag{2}$$

$$C = \frac{\varepsilon_r \varepsilon_o Kw}{h} \qquad (F / length) \tag{3}$$

where K is a fringe field factor [5] and Z_s is the film's surface impedance, which can be calculated by Mattis-Bardeen theory [6].

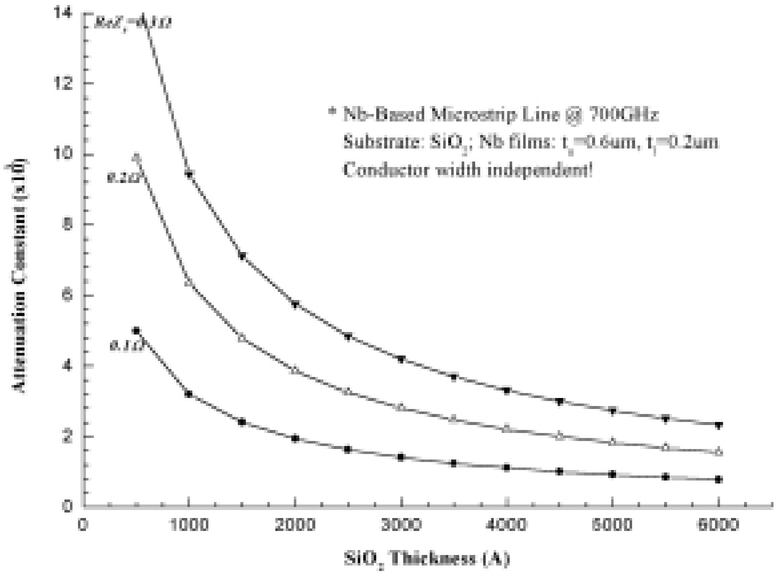

Fig. 1 Attenuation constant vs. substrate thickness.

The attenuation constant of Nb-based superconducting microstrip lines was studied for different insulation-layer thicknesses and conductor widths. The insulation layer in this case was assumed simply as one single SiO_2 layer. The calculation was done at 700 GHz for three examples of the real surface impedance $Re(Z_s)$ equal to 0.1, 0.2, and 0.3 Ω. It has been demonstrated that as plotted in Fig. 1, the attenuation constant is almost independent of the microstrip width, but decreases with the increase of the insulation-layer thickness (nearly saturated at a certain thickness).

2b. Twin junctions vs. end-loaded SIS

Two junction tuning circuits (refer to the insets in Fig. 2) were investigated to evaluate the effect of lossy thin-film microstrip lines on the performance of SIS mixers. One tuning circuit is commonly referred as the end-loaded type [7], while the other is parallelly connected twin junctions [8]. A quarter-wavelength impedance transformer was assumed in front of both tuning circuits to match a 35-Ω source impedance (i.e., the feed-point impedance of the mixer mount). The thin-film microstrip lines for the tuning inductance and impedance transformer were made up of two Nb films (0.6-μm thick for the wiring layer and 0.2-μm thick for the ground layer, assuming each an 0.1-Ω surface resistance) and a combined insulation layer as $Al_2O_3/SiO_2/Nb_2O_5$ (0.09/0.27/0.1 μm thick, ε_r=9/4/29).

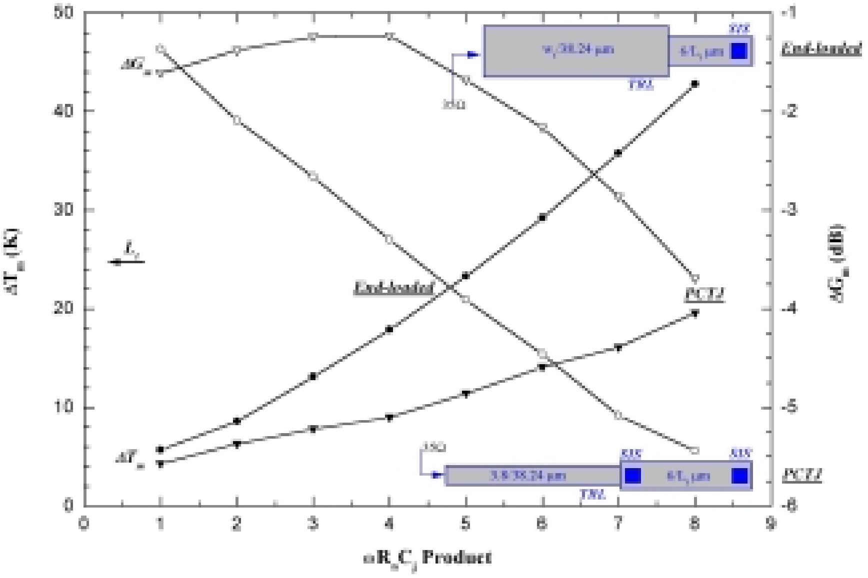

Fig. 2 Differences of the noise temperature and conversion gain as a function of junction's $\omega R_n C_j$ product.

The mixing performance (i.e., noise temperature and conversion gain) was simulated at 700 GHz for both tuning circuits. The junction's $\omega R_n C_j$ (with R_n fixed at 13.6 Ω) product was varied from one to eight for this simulation. Notice that after changing the junction's $\omega R_n C_j$ product we re-optimized the impedance-transformer width and the tuning-inductance length (indeed only the latter for the twin-junction case). Another simulation was done for the case of the thin-film microstrip lines without any losses for comparison. Fig. 2 demonstrates the noise temperature and conversion gain differences between the two simulated instances. Obviously, both the noise temperature and the conversion gain degrade while taking account of the film loss. Such performance deterioration is more evident for larger junction's $\omega R_n C_j$ product. It is interesting that for the end-loaded tuning circuit, the performance deterioration is rather sharp in comparison to the twin-junction circuit. We had found it was indeed caused by the transformer in the end-loaded tuning circuit, which has a larger impedance transforming ratio. It is also apparent that for both tuning circuits the conversion-gain difference is much larger than the total transmission loss of the thin-film microstrip lines (~1.6 dB per 153 μm). Lossy terminations at other frequency sidebands might contribute partly, as this difference depends strongly on the junction's $\omega R_n C_j$ product.

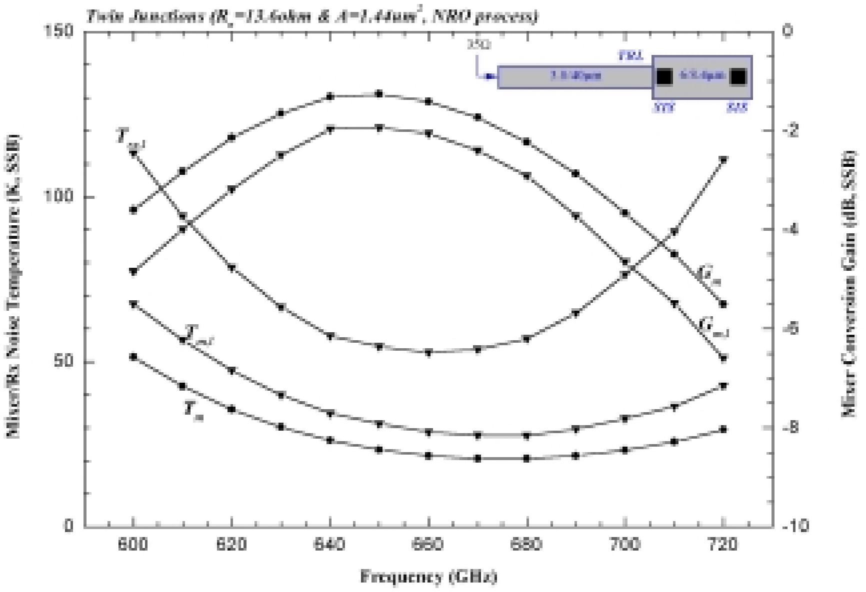

Fig. 3 Simulated Mixer performance for the 670-GHz SIS Mixer. Subcript m and m,l denote the mixer performance without and with the film loss taken into account, while subscript rx,l the receiver performance with the film loss.

2c. Simulated mixer performance

The twin-junction tuning circuit was adopted for the development of the 600-720 GHz SIS mixer, as it is less sensitive to the superconducting film loss than the end-loaded tuning circuit according to our simulation results. The junction's critical current density and area were taken as 10 kA/cm^2 and 1.2x1.2 μm, respectively. Correspondingly, the normal state resistance for individual junctions is 13.6 Ω and the junction's $\omega R_n C_j$ product is equal to

6.9 at 660 GHz by assuming a specific capacitance of 85 fF/μm^2. A quarter-wavelength impedance transformer, which has a width of 3.8 µm and a length of 40 µm, was utilized to match the twin junctions (of an input impedance equal to 6.8 Ω approximately) with the feed-point impedance of the mixer mount (~35 Ω). The tuning inductance between the twin junctions was optimized for the mixer performance by taking account of the loss effect of the superconducting films. Its width and length were found to be 6 µm and 8.4 µm, respectively. Fig. 3 exhibits the simulated mixer performance. Obviously, the receiver noise temperature (SSB) is less than 120 K in the frequency range of 600-720 GHz, with an assumption of 15-K IF noise temperature. It should be pointed out that the junction-chip structure was based on the fabrication process at Nobeyama Radio Observatory (NRO, as given in Section 2b).

3. Mixer Mount Simulation

The feed-point (refer to Fig. 4) impedance of the 660-GHz mixer mount was initially assumed to be 35 Ω (according to a scale model measurement [4]) for the mixer design. With the help of the Ansoft's HFSS simulator [9], we have calculated the feed-point impedance of the actual mixer structure including both choke filters on the IF and ground sides. The feed point was taken as a lumped gap source port (10.56µm x 2.0µm, «λ/10), while the waveguide and IF ports were the other two ports for simulation. All the structural parameters used here followed the original SAO design [4]. As plotted in Fig. 5a, the calculated resistance is well close to 35 Ω, while the reactance is around -30 Ω.

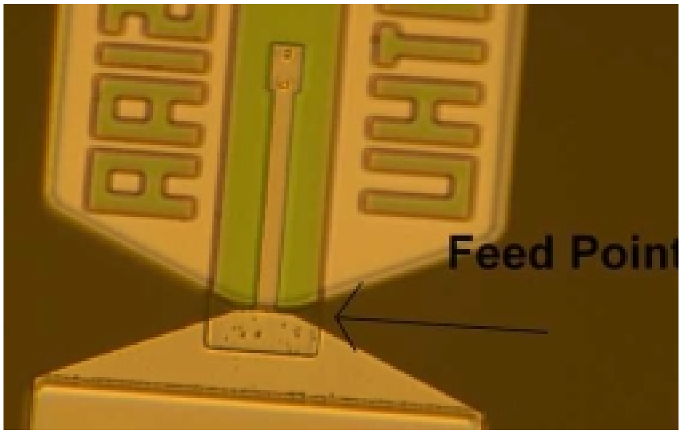

Fig. 4 Photograph of fabricated SIS junction at NRO.

We also studied the dependence of the feed-point impedance upon the size of the lumped gap source port, as the port size (mainly its width) is pre-assumed for HFSS simulation. As shown in Fig. 5b, the feed-point impedance varies with the width of the lumped gap source port. Given the fact that the lumped gap source port has a uniformly distributed field, we suggest its width should be taken exactly as that of the impedance transformer connected between the feed point and the junction tuning circuit. As it is well known, displacement often occurs when we align the SIS junction chip in the mixer mount. Hence we also examined the effect of the displacement of the feed point in waveguide. Calculation results have demonstrated that the impedance variation is not considerable for the feed-point position shift in both vertical and horizontal directions, but rather evident when the quartz-substrate thickness is reduced down to 30 μm from 40 μm.

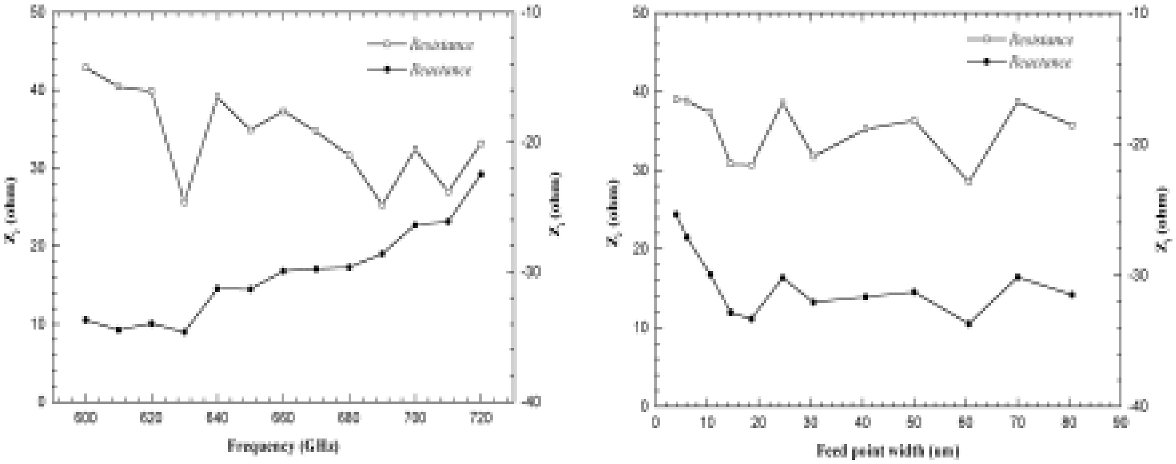

Fig. 5a Feed point impedance vs. frequency; Fig. 5b Feed point impedance vs. feed width

4. Experimental Results

The 660-GHz SIS junctions fabricated at NRO, which have a critical current density of about 10 kA/cm^2, were tested in a 640-GHz mixer mount [10]. It should be pointed out that due to over estimation of the junction shrinkage in the photomask the actual junction area was found approximately 30% larger than the design value, and that the feed-point impedance of the mixer mount used here is fairly close to that shown in Fig. 5a. The measured IF frequency was 6 GHz, at which the IF noise temperature is around 22 K. Fig. 6 shows the measured receiver noise temperature (DSB) from 618-660 GHz. Notice that there are no any corrections on the receiver noise temperature. Clearly the frequency response of the receiver noise temperature is shifted to a lower frequency than the designed center frequency of 660 GHz. The bandwidth appears not clear because of a limited frequency coverage for this measurement. In spite of that, we did observe a noise temperature of 145 K around 620 GHz.

Given the fact the twin SIS junctions had a larger area, we indeed tested the twin junctions of a tuning inductance which is 30% shorter than the designed length. The frequency response of the measured receiver noise temperature, however, was not well compensated, just as shown in Fig. 6. There are two possible causes for this frequency shift. One is a narrower wiring layer for the tuning inductance (i.e., of a higher characteristic impedance) due to over etching, and the other is a parasitic inductance being around individual SIS junctions (of non-uniform current distribution for a relatively large area). In terms of the resonance steps observed on the junction’s I-V curve (refer to Fig. 7), we can estimate the resonance frequency of the twin-junction tuning circuit. Therefore, it may be possible to extract the junction’s parasitic inductance by comparing the measured resonance frequency with the one derived form an equivalent circuit model for the twin-junction tuning circuit including the parasitic inductances.

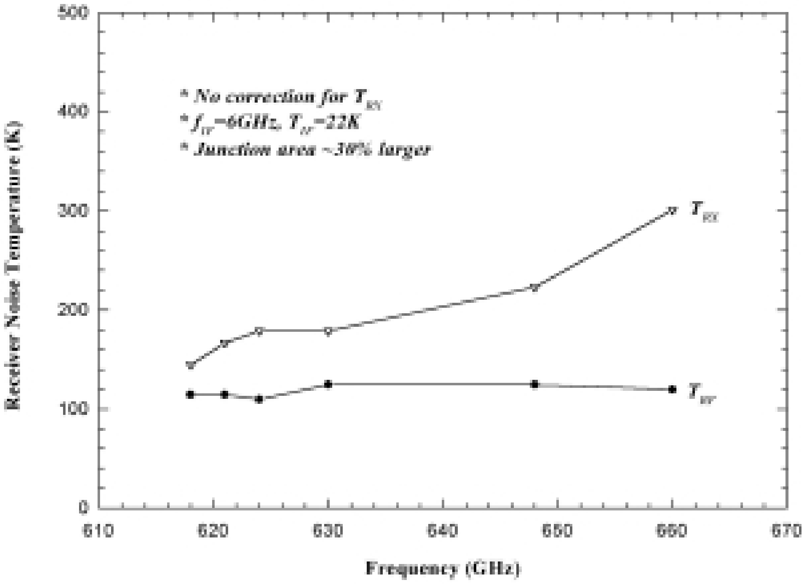

Fig. 6 Measured receiver noise temperature (DSB) for the 660-GHz SIS mixer.

5. Summary

We have designed a 600-720 GHz SIS mixer using Nb twin junctions, with the surface impedance rise of Nb films beyond its gap frequency taken into account. The simulation results are quite promising, giving a receiver noise temperature (SSB) of below 120 K. The feed-point impedance of the 660-GHz mixer mount is well understood through HFSS simulations. A preliminary experiment has demonstrated a receiver noise temperature as low as 145 K at 618 GHz, although its frequency response is still far from satisfied.

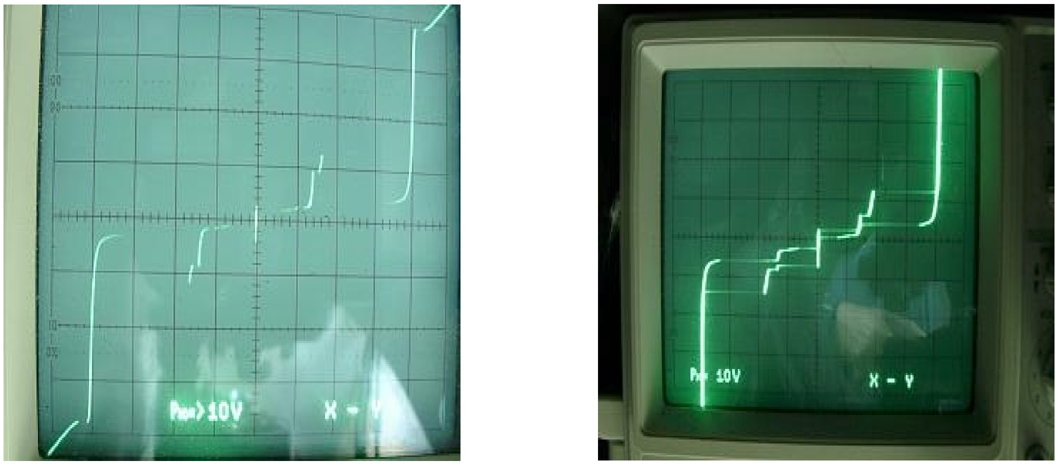

Fig. 7 I-V curves of the twin junctions (a: with a design tuning inductance; b: with a 30% shorter one; 0.677mV/div)

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