A FIXED TUNED LOW NOISE 600–700 GHZ SIS RECEIVER

C. C. Chin, 1,* M. J. Wang, 1 W. L. Shah, 2 W. Zhang, 2 H. W. Cheng, 1
S. C. Shi, 2 and T. Noguchi 3

1Institute of Astronomy and Astrophysics
Academia Sinica, Nankang, Taipei
Taiwan, China
2Purple Mountain Observatory, Nanjing, China
3Nobeyama Radio Observatory, NAOJ, Nobeyama
Nagano 384-13, Japan

*Present address: Herzberg Institute
5071 West Saanich Road
Victoria, BC, Canada V9E 2E7
E-mail: chi-chung.chin@nrc.ca

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Abstract

We have designed and fabricated a fixed tuned low noise 600-700 GHz SIS mixer. Twin junctions connected in parallel was employed in the mixer design. A short microstrip tuning structure was used to minimize the RF signal loss at frequency above the energy gap. A receiver noise temperature below 200 K (without any loss correction) in the frequency range of 630 to 660 GHz was recorded. The lowest noise temperature of the receiver was 181 K (without any loss correction) at 656 GHz.

Keywords : Sub-mm-waves, SIS mixers and Receivers.
INTRODUCTION

Havard-Smithsonian Center of Astrophysics (CFA) is building a sub-mm array (SMA) with six telescopes. The Institute of Astronomy and Astrophysics (IAA) of Academia Sinica is extending the array by two additional telescopes. We have developed a fixed tuned low noise 600-700 GHz receiver for these two additional telescopes of SMA.

The frequencies higher than 650 GHz are above the frequency energy gap of Nb at 4.2 K. It has been shown that Nb-AlOx-Nb junctions work well and low noise SIS receivers were successfully built at the frequencies up to the energy gap of Nb. At the frequencies above the gap, the RF signal loss and the surface impedance increase due to the breaking of Cooper pairs as predicted by Mattis-Bardeen Theory [1]. The noise of SIS receivers increases rapidly at frequencies above the gap.

Several attempts have been tried to obtain a low noise 600-700 GHz SIS receiver. Excellent results were reported. Tong et al. [2], [3] reported a fixed tuned low noise SIS receiver for the 600 GHz frequency band using an end-load lump and a distributed junction respectively. Kooi et al. [4] reported a non-fixed tuned 665 GHz receiver using a 0.5 \( \mu m^2 \) Nb/AlOx/Nb SIS junction. Gaidis et al. [5] reported a 600 GHz quasi-optical SIS mixer.

In this paper, we have designed and fabricated a fixed tuned waveguide low noise 600-700 GHz Nb SIS receiver. Twin junctions of size of 1.2 \( \times \) 1.2 \( \mu m^2 \) connected in parallel were utilized. A receiver noise temperature below 200 K in the frequency range of 630 to 660 GHz was recorded. It went up to 263 K at 680 GHz, which was above the Nb gap frequency. The lowest DSB receiver temperature of 181 K at 656 GHz was achieved. There is no loss correction on the measured receiver noise temperature.
DESIGN AND FABRICATION

The design of the corrugated feed horn, mixer block, choke filter and the probe followed those of Tong et al. [3] except the substrate thickness was changed to 41\(\mu\)m [10]. Our junction design was twin junctions connected in parallel through a Nb microstrip line [7], [8], [9] as shown in Fig. 1. The junctions were fabricated at Nobeyama Radio Observatory using the selective Nb etching process [6], which incorporated the anodization of Nb to form a layer of Nb$_2$O$_5$ around the junction to reduce the sub-gap-leakage current. SiO$_2$ and Al$_2$O$_3$ thin films were deposited as the insulating layers between the Nb microstrip line and ground plane. At frequencies above the Nb energy gap, the breaking of the Cooper pairs by the RF photons results in a greater
signal loss, and hence the receiver temperatures. This RF signal loss is particularly important in the Nb microstrip used to resonate the junction capacitance. Care was taken in the design to minimize the RF signal loss in the Nb microstrip. Shi et al. [12] have shown that the RF signal loss decreases as the dielectric thickness increases. In our design, we chose the maximum dielectric thickness, which could be deposited by our sputtering system with high quality. The thickness of the dielectrics Nb$_2$O$_5$, SiO$_2$ and Al$_2$O$_3$ were 0.1, 0.27 and 0.09 μm respectively. A shorter tuning microstrip will yield a smaller signal loss and hence a lower receiver noise temperature. To shorten the length of the tuning structure, junctions with high critical current of 10 KA/cm$^2$ and size of 1.2 x 1.2 μm$^2$ were chosen. It gave the normal state resistance of a single junction at 4.2 K, $R_N$ and the product, $\omega R_N J_c$ equal to 13.6 Ω and 6.9 respectively. A Nb microstrip transformer of a width of 3.8 μm transformed the resulting impedance to a feed point embedding impedance of 35 Ω [11]. Quartz crystal substrates were used.

Figure 2. The simulation of the performance of the mixer designed.
Fig. 2 shows the simulation result of the performance of the mixer. No input noise was included in this calculation. Quasi-five-port model [13] was used in the simulation. The noise temperature of the HEMT amplifier was assumed as 15 K during the simulation.

**EXPERIMENT SETUP AND JUNCTION CHARACTERIZATIONS**

The noise measurement system was a standard setup. The RF signal was convergent to the mixer by an off-axis concave mirror. The signal from the local oscillator (LO) was partially reflected by a wire grid. The plane of the wire grid was put at 45 degrees to the optical axis of the concave mirror. The angle of the wire grid can be rotated to adjust the amount of LO power injected into the mixer, and hence to determine the level of the front end input noise temperature. The optical window was a 23 μm thick mylar. A thin Zitex foil at the physical temperature of 77 K placed behind the optical window was used as the infrared filter. The IF output of the mixer was amplified by a low noise 4-6 GHz HEMT amplifier. The noise temperature of the mixer was measured by the conventional hot/cold load method.

In order to offset any shrinkage of the junction size in the fabrication process, in addition to the original designed value of the length of the tuning structure, we put junctions with the length of the tuning structure different from the original length by ±30% on the photolithography mask. Therefore, we obtained junction chips with a tuning structure length of 0% and ±30% of the original design on the same wafer. Table I summarizes the characterizations of the junctions measured. Sample 1 was fabricated in the first batch with a larger junction size on the photolithography mask and thus gave a smaller $R_N$. The junction size on the mask was then readjusted in the second fabrication batch for sample 2 and 3. Table II summarizes the mixers tested using different combination of junctions and mixer blocks. Horn and mixer blocks #1 and 2 were fabricated using exactly the same design by two different highly respected vendors in this field respectively. Physical examination on these two horns and mixer blocks revealed that all the
outside dimensions of the horn and mixer block that we could measure agreed with the specifications of the design.

<table>
<thead>
<tr>
<th>Junction Sample #</th>
<th>$R_N$ (Ω)</th>
<th>$R_s/R_N$ (Ω)</th>
<th>Tuning Length</th>
<th>Batch #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.2</td>
<td>17</td>
<td>-30%</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>11</td>
<td>0%</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>8.7</td>
<td>0%</td>
<td>2</td>
</tr>
</tbody>
</table>

Table I. The summary of the normal state resistance at 4.2 K, $R_N$, the ratio of sub-gap resistance to the normal state resistance, $R_s/R_N$, the length of the tuning structure and the corresponding fabrication batch # of different junction samples tested.

RESULTS AND DISCUSSIONS

Fig. 3 shows the DSB receiver noise temperature of the different mixers listed in Table II. During the noise temperature measurement, the wire

![Graph](image_url)

Figure 3. The DSB receiver noise temperature of different mixers.
grid was set at 20 degrees to the horizontal measured in the plane of the wire grid itself unless otherwise stated. The corresponding power reflection coefficient for the LO was approximately 20%. It turned out that junctions with tuning length of 0% gave the right noise temperature response. Mixers A, B, and D have a receiver noise temperature between 200 and 450 K across the band while it is below 300 K in the frequency range of 620 to 690 GHz. Mixer B gives the lowest noise temperature of 220 K at 656 GHz. The noise temperature of mixer C is too high due to the much smaller value of R_N and is not shown in Fig. 3 for clarity. Its other properties will be discussed later.

The noise temperature of mixer B was measured again with the wire grid set at 10 degrees to the horizontal to decrease the front end input noise. The corresponding power reflection coefficient for the LO was about 6%. A receiver noise temperature below 200 K in the frequency range of 630 to 660 GHz was recorded. The lowest noise temperature of the receiver was 181 K at 656 GHz. The noise temperature went up to 263 K at 680 GHz. However, the LO did not have enough power to measure the noise temperature above the frequencies of 680 GHz while the wire grid angle was set at 10 degrees.

The front end input noise temperature at a particular frequency was determined by measuring the IF output at different LO powers [16], [17]. Fig. 4 shows the front end input noise temperature of different mixers with the wire grid set at 20 degrees. The input noise

<table>
<thead>
<tr>
<th>Mixer #</th>
<th>Junction Sample #</th>
<th>Horn and Mixer Block #</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
temperatures for all the mixers are higher at lower frequencies.

![Graph showing front end noise temperature for different mixers.](image)

Figure 4. The front end noise temperature for different mixers.

In general, mixers using horn and mixer block #1 have a lower input noise temperature than that of horn and mixer block #2. Mixers A and D used exactly the same junction of sample #1 but were composed of a different horn and mixer blocks #2 and #1 respectively. The input noise of mixer D is less than that of mixer A especially at the lower frequency range 600 to 640 GHz. The difference of input noise can be as large as 116 K at 612 GHz. It demonstrated that although both horn and mixer block #1 and #2 used the same design, the resulting noise performance of the two horns and mixer blocks were quite different. It might depend on the manufacturing quality. However, it is still unknown what kind of manufacturing factors should be improved in order to get a lower noise temperature.

Fig. 5 shows the noise performance of mixers A, B, and C in the frequency range of 450 to 490 GHz. A dip in the frequency dependence of the noise temperature in the frequency range from 470 to 485 GHz
was observed. A noise level of about 300 K was obtained at the dip.

![Graph](image)

Figure 5 The DSB receiver noise temperature of different mixers in the frequency range of 450 to 490 GHz.

It demonstrates that there is an additional resonance at the frequencies from 470 to 485 GHz. It should be noted that all the mixers A, B, and C use the same horn and mixer block #2. Mixer D utilized the same junction as that of mixer A but used horn and mixer block #1. Serious attempts have been carried out to measure the noise temperature of mixer D in the frequency range from 450 to 500 GHz. Noise temperatures of several thousands K were measured. The same results were observed for all other mixers composed of horn and mixer block #1. It demonstrates that there is no additional resonance at the 480 GHz range for horn and mixer block #1. We have a chance to measure the FTS of mixer C. The FTS shows an additional peak at 480 GHz as shown in Fig. 6. It agrees with the noise temperature measurement.
The reason for this additional 480 GHz peak is not clear yet but is believed to be related to the mixer block itself. We speculate that there may be an additional inductance path in mixer block #2 arisen from the manufacturing process giving an additional resonance at 480 GHz. It also demonstrates the importance to control the quality of the mixer blocks to give the right noise response. Nevertheless, once we understand these properties, we may open a door to fabricate dual band mixers although the noise temperature at 480 GHz is still quite high now.

We have demonstrated that parallel-connected twin junctions structure can be optimized to get a low receiver temperature of 181 K at 636 GHz. However, we believe that it is possible to even achieve a lower noise temperature. We should point out that although our target substrate thickness was 41 μm, our resulting substrate thickness was about 30 μm. The thinner substrate thickness was due to the inaccuracy of our lapping process. Effort is being carried out to improve the
lapping accuracy. Since the dielectric constant of Quartz substrate is 4.45, which is quite high, a change of substrate thickness may change the embedding impedance at the feed point [14]. Fig 7 shows the embedding impedance for a 30 μm thick substrate as calculated by the HFSS software [15]. It is deviated from the 35 Ω. The Quasi-five ports

![Graph showing embedding impedance vs frequency](image)

**Figure 7.** The embedding impedance of the mixer block for a quartz substrate thickness of 30 μm calculated by HFSS.

model shows that the DSB noise temperature of the receiver is increased by approximately 25 K due to the change of the substrate thickness of 41 μm to 30 μm as calculated using the embedding impedance obtained by the HFSS software. Lower noise temperature can be obtained if we can improve our lapping process and keep the substrate thickness to 41 μm. Furthermore, decreasing the leakage current of the junction and improving the accuracy of junction size should help to decrease the noise temperature. Efforts on improving the receivers in the directions discussed above are being carried out.
ACKNOWLEDGMENT

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