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Performance Characterization of a 600-700 GHz SIS Mixer

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Abstract

A 600-700GHz SIS mixer with the twin-junction tuning circuit has been designed and fabricated [1]. The surface impedance of thin-film superconducting microstrip lines, based on Mattis-Bardeen theory [2], is included in the optimization of RF impedance matching. The receiver noise temperature measured in the frequency range of 630-660GHz is below 200K and the lowest receiver noise temperature of 181K is achieved at 656GHz. The FTS response of the SIS mixer shows a good RF coupling from 600GHz to 700GHz. Both the noise performance and the FTS response can be quantitatively described by numerical results using the quantum theory of mixing. Some detail considerations on the mixer model calculation, such as spreading inductance around the junction tuning structure and mixer's embedding impedance, are discussed.

Introduction

Nb-based superconductor-insulator-superconductor (SIS) mixers have been used very successfully in sub-mm wavelength detection. Their receiver noise temperature has reached to three times the quantum limit, ~3 hf/k_B, below the junction's gap frequency. However, at high frequency bands, Nb SIS mixers need to be designed carefully because the photon energy is close to or higher than the gap energy of Nb, Δ~1.4meV. When the frequency band covers the gap frequency of Nb, ~670GHz, the RF loss of Nb superconducting transmission lines increases dramatically and the surface impedance has strong frequency dependence. Usually, the RF properties of a superconducting transmission line can be described by the Mattis-Bardeen theory [2] in good accuracy. From results reported so far [4-9], the best receiver noise temperature is close to 5 hf/k_B in the band of 600-700GHz. Despite of the input loss contributed by the experimental setup, some other properties of SIS mixers should be taken into account. In this paper, we characterize the performance of a 600-700GHz mixer by comparing the experimental and simulated results.

Mixer design

The embedding impedance of the 600-700GHz SIS mixer was calculated by HFSS using the structure of the SMA mixer block and RF choke, which are designed by the receiver team at SAO, but with a substrate thickness of 30μm. Figure 1 shows the calculated embedding impedance over the interesting frequency band. Both the real and imaginary parts of the impedance vary remarkably in the band of 600-700GHz. This variation of the embedding impedance should be considered in the mixer performance calculation.

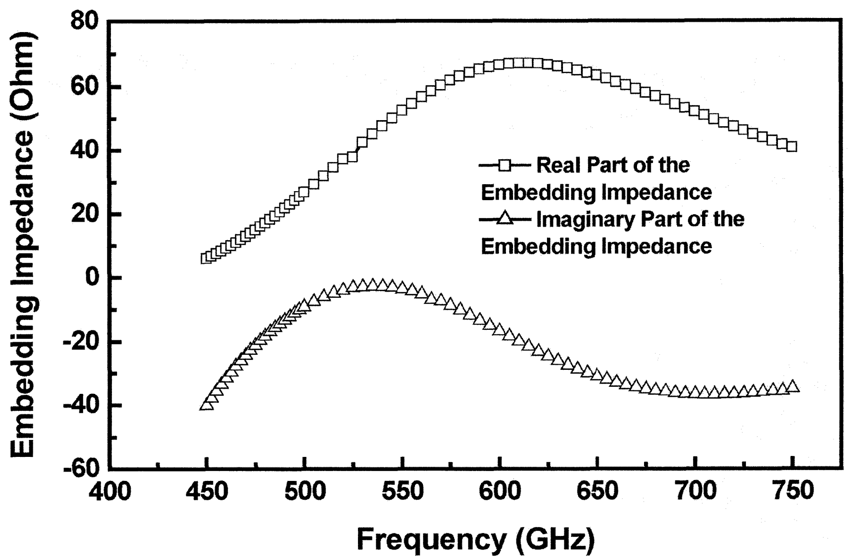

Fig. 1 Embedding impedance of the 600-700GHz SIS mixer calculated by HFSS.

The junction circuit design was based on a PCTJ (Parallel Connected Twin Junction) structure [10]. The designed parameters for the SIS junction as well as the transmission line structure are shown in Fig.2. To consider the capability and reliability of fabrication, the junction size was kept as large as possible, 1.2×1.2 μm^2 in this case. The designed J_C was 10 kA/cm^2 and the junction's specific capacitance was assumed to be 90 $fF/\mu m^2$. The superconducting transmission line was based on $Al_2O_3/SiO_2/Nb_2O_5$ trilayer dielectric with thickness of 900Å/2700Å/1000Å. In addition, the RF surface loss of superconducting films is no more negligible when photon energy is close to or higher than the gap energy of superconductor. For niobium-based devices, the gap frequency is near 670GHz (Δ~1.4 meV), which is just in the frequency band of interest. According to

Junction design parameters

Single Junction Parameters (design)

J_c=10kA/cm^2

A=1.2x1.2μm^2

C_j=1.44μm^2 x 90fF/μm^2=129.6fF

R_n=13.54Ω (by I_cR_n=1.95mV)

Impedance transformer

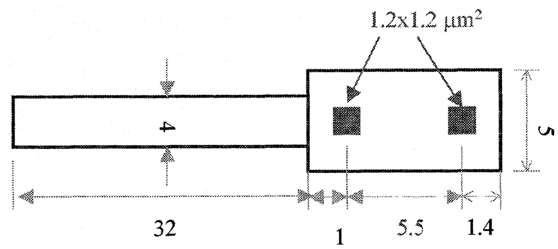

Fig. 2 Designed SIS junction parameters and the transmission line structure near junction, in μm unit. The J_C is 10 kA/cm^2 and the junction specific capacitance is assumed to be 90 fF/μm^2. Two 1.2×1.2 μm^2 junctions are connected by a 5.5μm wide superconducting transmission line to tune out the junction's geometric capacitance.

Mattis-Bardeen theory [2], the RF losses of the superconducting transmission lines were included during the optimization procedure of RF impedance matching [11].

Experiments

The SIS junction was fabricated by selective niobium etching process with additional anodization technique [12]. The Nb/AlO$_x$-Al/Nb (1000Å/70Å/2000Å) multi-layer was *in-situ* deposited on crystal quartz wafer with RF choke photo-resist lift-off pattern. The Al layer was exposed to 25 mtorr of Ar/10%O$_2$ mixture for 30 minutes to obtain critical current density (J_C) of 10kA/cm^2. The junction was defined by Deep UV source of mask aligner and top Nb was etched by RIE system using CF_4+O_2 mixture as processing gas. Before the deposition of the insulator layer, an additional anodization process was applied to anodize about 300Å thick Nb around the junction. An insulating layer of SiO$_x$/AlO$_x$ (2700Å and 900Å) was deposited as the dielectric of the superconducting transmission lines. Before the deposition of a 6000Å thick wiring Nb film, the native oxide on top Nb surface was removed by applying Ar plasma. A 200Å/2000Å thick Ti/Au film was deposited on the contact pad of chip to reduce the contact resistance of DC/IF leads. Then, the quartz substrate was thinned by lapping machine and diced into individual chips, measuring 2mm (L) by 150μm (W) by 30μm (T).

The mixer performance was measured in a liquid He cooled dewar using typical hot/cold load technique. Fig. 3 shows the schematic drawing of the testing system. The LO source was generated by a multiplier (doubler+tripler) pumped by Gunn oscillator. Its frequency coverage is from 600GHz to 700GHz. The wire grid angle was set at 20° to couple enough LO power. However, it will increase the input RF noise temperature. Smaller grid angle was also tried to obtain lower receiver noise temperature in a narrow frequency range limited by insufficient LO power. The RF signal and LO power passed through a mylar vacuum window and Zitax IF filter, then were reflected by a cooled off-axis parabolic mirror into the corrugated horn of the mixer block. The IF signal was magnified by a cooled low noise amplifier (LNA) in the dewar and by a post amplifier at room temperature, then detected by a HP48xx power detector. Magnetic field by a superconducting coil was applied to reduce the Josephson tunneling effect. The hot/cold load was provided by a black body emitter at temperature of 295K/77K. The FTS measurement was done in the laboratory of National Astronomical Observatory of Japan at Mitaka. To get more reliable information, we used the same mixer block and junction in FTS and T_{rx} measurement.

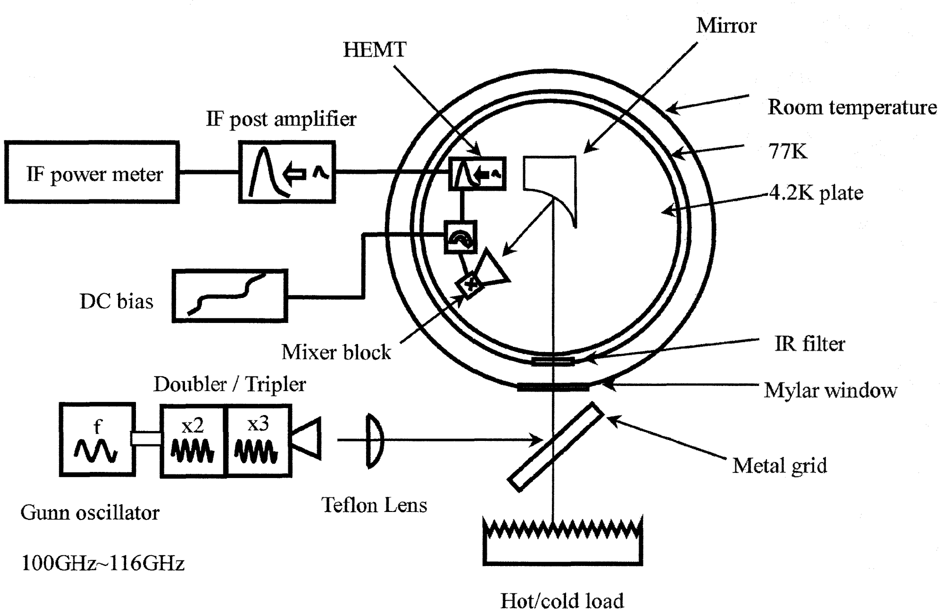

Fig. 3 Schematic drawing of the mixer performance testing system.

Results and discussion

The mixer noise performance is shown in Fig. 4. The solid circle is the simulated mixer noise temperature without any additional correction of the embedding impedance (simply assumed to be 35Ω here). Obviously, the center frequency is around 670 GHz. The data of sample Mixer A, Mixer B, and Mixer E (open square, down triangle and diamond points) are experimental results with a wire-grid angle of 20° . The un-corrected receiver noise temperature, T_{rx}, is below 300K in the frequency range of 600-680GHz. The center frequency of the mixer noise performance is shifted to 650GHz. The lowest T_{rx} is near 230K around 650GHz. It should be noted here that the quick rise of T_{rx} in the band edge was due to insufficient LO power. The solid triangle is exactly the same experiment of sample Mixer A, but with a wire-grid angle of 10° . The noise temperature is reduced significantly in the frequency range of 630GHz to 670GHz. The lowest noise temperature can reach to 181K at 656GHz. This performance improvement is attributed to the reduction of the RF input noise temperature from the wire grid. It can be roughly estimated from the power loss of the RF signal due to the

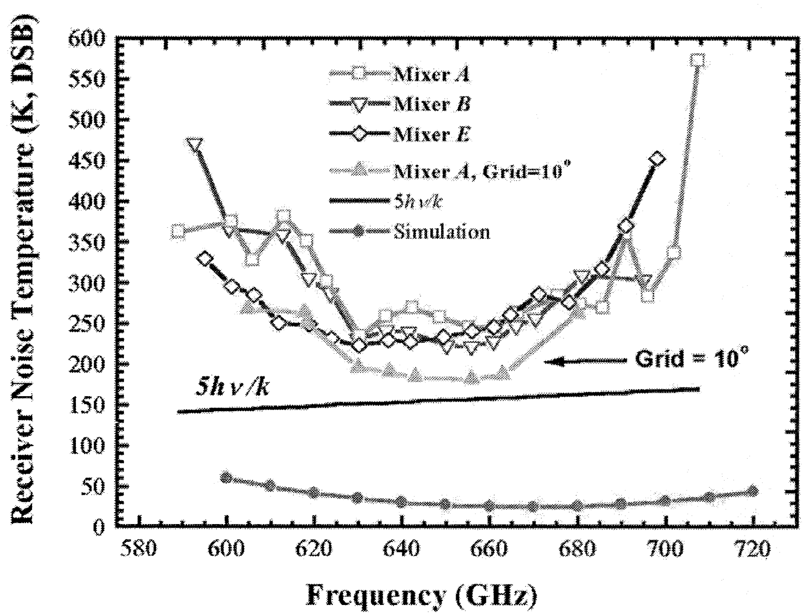

Fig. 4 Measured and simulated receiver noise temperature of the 600-700GHz SIS mixer. The solid circle is the simulated mixer noise temperature without any additional correction of the embedding impedance. The open square, down triangle and diamond points (Mixer A, Mixer B, and Mixer E) are the experimental results with wire grid at 20° . The solid triangle is exactly the same experiment of sample Mixer A but with wire grid at 10° .

misalignment between the waveguide polarization and the wire grid angle. The effective angles of the wire grid projected onto the waveguide polarization direction are about 25.8° and 13.8° for setting at 20° and 10° on the grid's holder, respectively. It is well known that the input noise of an object is equal to $T_{amb} \times \alpha$, where T_{amb} is the physical temperature of object and α is the absorption coefficient. Thus, the input noise temperature contributed from the wire grid is about 56K and 16K for the cases of the wire grid set at 20° and 10° on the grid's holder, respectively. The 40-K reduction of T_{rx}, due to the wire grid angle changed from 20° to 10°, is consistent with the experimental results.

The FTS experiment could reveal the relative coupling strength between RF signal and mixer. The measured time domain FTS response is shown in Fig. 5. The SIS mixer was biased at 1.9mV that is similar to the value for the T_{rx} measurement. The nice FTS response curve in time domain will give a more reliable frequency response after Fourier transformation.

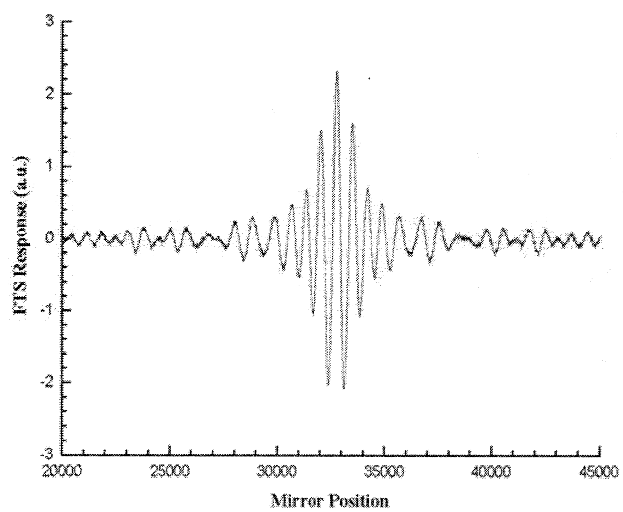

Fig. 5 Time domain FTS response measured for the 600-700GHz SIS mixer biased at 1.9mV.

Fig. 6 shows the FTS response of the 600-700GHz SIS mixer, the solid circle points, in a frequency range of 400GHz to 800GHz. The T_{rx} result of the same receiver is also plotted in the figure, down triangles, for comparison. The FTS response is relatively strong from 600GHz to 700GHz and from 470GHz to 510GHz. There is a strong absorption of water around 550GHz, which will reduce the FTS response. In general, the FTS response is consistent with the mixer performance result. The up-triangles are the simulated result of the RF coupling. An additional length of 2x1μm (2ΔL) in tuning inductor, about 40% increase in length of the original design, was added during the simulation. We found that the FTS response can be described qualitatively by the simulation result. The origination of this additional inductance might be due to the spreading current effect near small SIS junctions because of their low impedance comparing with the transmission line. It may need more experiment to understand the contribution of this effect.

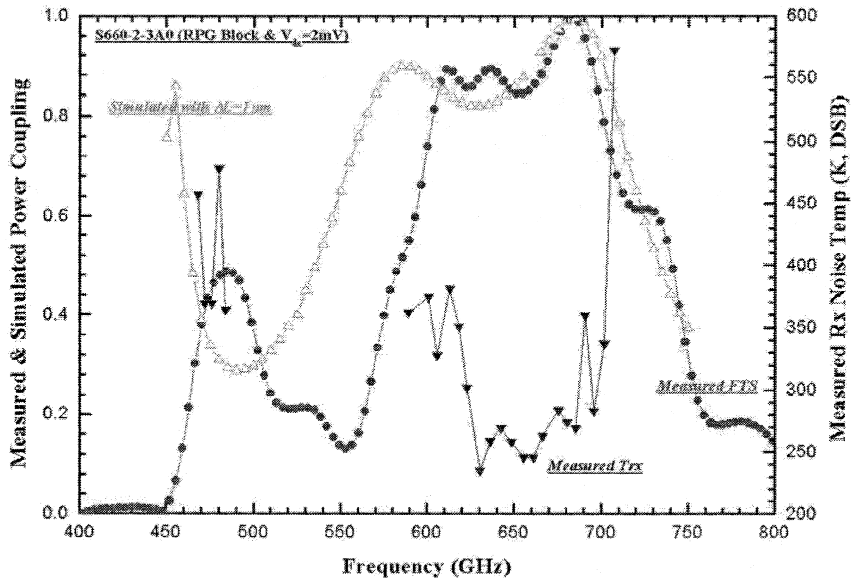

Fig. 6 Measured FTS response of the 600-700GHz SIS mixer, the solid circles. The down-triangles are the T_{rx} value of the same receiver. The FTS response is basically consistent with the performance of receiver. The up-triangles are the simulated results with additional 1mm of tuning structure. The FTS response can be qualitatively described by the simulation result. The additional inductance might be originated from the spreading current effect near SIS junction.

Conclusion

Low noise SIS receivers for 600-700GHz have been achieved using PCTJ type mixer. The un-corrected double-side-band noise temperature is below 300K in this frequency band. The variation of the embedding impedance and the RF loss of the thin-film transmission lines are taken into account in the simulation model. However, the lowest noise temperature is only close to $5hf/k_B$. The FTS result shows a consistent frequency window of the RF coupling as T_{rx} experiment. The simulated RF coupling can qualitatively describe the FTS experimental result by adding an extra inductor. This additional inductor might result from the current spreading effect near the SIS junctions. More experimental results are necessary to clarify its origination.

Acknowledgement

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