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Development of an SIS(Superconductor-Insulator-Superconductor) Junction Mixer over 120~180 GHz Band

120~180 GHz 대역 SIS(Superconductor-Insulator-Superconductor) 접합 믹서의 개발

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Abstract

A fixed-tuned SIS(Superconductor-Insulator-Superconductor) mixer across 120~180 GHz band has been developed. This mixer employs an SIS chip fabricated by Nobeyama radio observatory which consists of a series array of 6 Nb/Al-Al_2O_3/Nb junctions in a microstrip line on a fused quartz substrate. The SIS chip is placed at the center of the half-height waveguide mixer mount to have a good incoming signal coupling over the whole frequency band. No mechanical tuner was used in the SIS mixer and the RF signal and local oscillator power are injected to the mixer via a cooled cross-guide coupler. In order to prevent the IF signal loss, the IF output impedance of the SIS mixer was matched to the 50 Ω input impedance of the IF chain. Measured double sideband noise temperatures of a receiver using the SIS mixer are 32~131 K over 120~180 GHz band. The developed SIS mixer is now in use for radio astronomical observations on the TRAO 14 m radio telescope.

요 약

120~180 GHz 대역의 고정 튜닝방식을 사용한 SIS(Superconductor-Insulator-Superconductor) 접합 믹서를 개발하였다. 이 믹서는 노베야마 전파천문대에서 제작된 6개 직렬 연결 Nb/Al-Al_2O_3/Nb SIS 접합 소자를 사용하였으며 석영유리 기판에 제작된 이 SIS 칩은 전 주파수 대역에서 입력신호 결합을 향상시키기 위해 half-height 도파관의 중심에 놓여 있다. 본 논문에서 개발된 SIS 믹서는 기계적인 튜닝 장치를 사용하지 않으며 RF 신호와 LO 전력은 냉각된 십자형 방향성 결합기를 통해서 믹서에 공급된다. 또한 IF 신호 손실을 줄이기 위해 SIS 믹서의 IF 출력 임피던스를 IF 증폭단의 50 Ω 입력 임피던스에 정합 시켰다. SIS 수신기의 측정된 DSB 잡음온도는 120~180 GHz 대역에서 32~131 K이며 본 논문에서 개발된 SIS 믹서는 대덕전파천문대의 14 m 전파망원경에 설치되어 전파천문 관측에 사용되고 있다.

Key words : SIS Junction, Millimeter-Wave Mixer, Heterodyne Receiver, Radio Astronomy

Ⅰ. Introduction

The SIS mixer is the most sensitive heterodyne detector at millimeter and submillimeter wavelengths. Since it was introduced in the early 1980s, heterodyne receivers employing SIS mixers have been a powerful tool for millimeter and submillimeter wavelengths spectroscopic radio astronomy. The SIS junction is made up of a sandwich of two superconductors separated by a thin insulator through which quasi-

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particles tunnel from one superconductor to another. The quantum theory of heterodyne mixing was developed by Tucker[1] and became the theoretical framework to understand and design the SIS mixers. Compared to the classical heterodyne mixers like Schottky diode mixer, the SIS mixer has extremely low noise limited by the quantum noise and needs very low LO(Local Oscillator) power. Now the SIS receivers are the heterodyne detectors of choice used in almost all of the millimeter and submillimeter-wave radio astronomy observatories in the world[2].

TRAO(Taeduk Radio Astronomy Observatory) has utilized two kinds of SIS mixer over 86～115 GHz and 120～180 GHz bands for several years. But the SIS mixer for 120～180 GHz band has suffered from higher receiver noise temperatures above 160 GHz, which restricted the radio astronomical observation for 160～180 GHz band. This problem motivated us to develop a new SIS mixer which would enable radio observations over the whole 120～180 GHz band. The development of SIS mixers generally consists of two critical parts: SIS chip and mixer block designs. Since we have no facilities needed for fabricating superconductor thin films, the SIS chips already fabricated in Nobeyama radio observatory were employed in our SIS mixer design. Although this fact limited our mixer design option, a good performance of the SIS mixer could be achieved by carefully choosing the mixer block structure based on simulation results.

This paper describes our SIS mixer design approach and some experimental results of the developed SIS mixer in the frequency range 120～180 GHz.

Ⅱ. Design of the SIS Mixer

The SIS chip used in the mixer was designed and fabricated by Nobeyama radio observatory several years ago[3]. The SIS chip contains six SIS junctions connected in series, low pass filter(or RF choke) and bow-tie probes as a means of coupling the incoming RF signal and LO power from the input waveguide into the SIS junctions on a substrate(fused quartz, $\varepsilon_r = 3.8$). In fact the SIS chip should be designed in parallel with the mixer block to optimize the overall performance of the SIS mixer but in this paper, it was imperative for us to make a mixer block mount using the SIS chip designed for other mixers. The size of the six SIS junctions each is $1.75 \times 1.75\ \mu\text{m}^2$ and the junction's specific capacitance due to the sandwich structure of the SIS junction is assumed to be 90 fF/μm^2. The normal state resistance of the SIS junctions was designed to be about 100 Ω but it depends on the process of fabrication[3]. Since the SIS chip has no inductive tuning circuit to compensate the junction's geometric capacitance, the RF coupling efficiency may be poorer than the SIS mixers with which the tuning circuits are integrated. Generally the SIS mixer with no inductive tuning circuit has narrower operation bandwidth unless backshorts or mechanical tuners are retuned at operating frequencies [4],[5]. The previous SIS mixer for 120～180 GHz band has employed the full height waveguide as a mixer mount in which the SIS chip was located. As several authors have investigated and mentioned in [6]～[9], this mixer mount configuration causes a resonance within the operating frequency band due to the cross-modal coupling[6]. Fig. 1 describes the equivalent circuit model of the SIS mixer mount. In Fig. 1 the embedding impedance(Z_{emb}) is defined as the impedance seen by the SIS junctions mounted inside the waveguide. Z_{rf} and C_J are the RF impedance and the geometric capa-

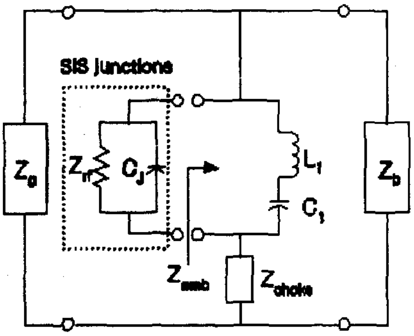


Fig. 1. Equivalent circuit model for the SIS mixer mount.

citance of the SIS junctions. C_1 and L_1 are the capacitance due to TM_{m1} mode and the inductance due to TE_{m1} mode. The waveguide, backshort impedances and the impedance due to the SIS chip's RF choke are Z_g, Z_b, and Z_{choke}, respectively.

For the SIS mixer to operate efficiently with wide bandwidth, the embedding impedance must have only a constant real part over the desired operation band. The resonance frequency due to the cross-modal coupling can be sufficiently pushed out of the operating frequency band by reducing the waveguide height. Considering the fabrication complexity of the mixer block, the height of the waveguide mount is reduced by half in order to avoid that resonance frequency. As shown in Fig. 2, the SIS chip is mounted at the center of the half-height waveguide.

Fig. 3 shows the calculated return losses using 3D EM simulator(HFSS) at the feed point where the SIS junctions are placed. It was found that there is little difference in the return losses by varying the gap distance between tips of the bow-tie probe. The real part of the embedding impedance is around 38 Ω and the imaginary part varies from −20 Ω to 7 Ω across 120~180 GHz band.

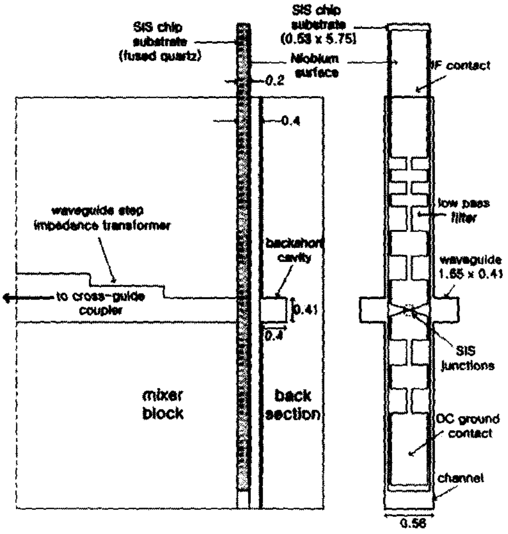


Fig. 2. Mixer block structure(unit: mm) and SIS chip.

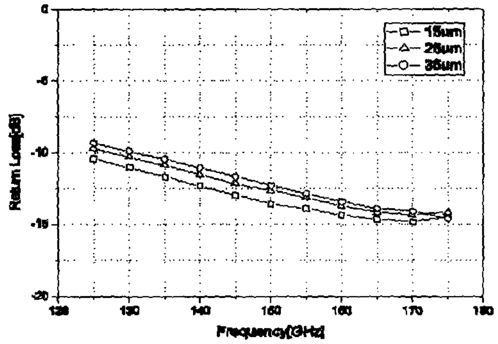
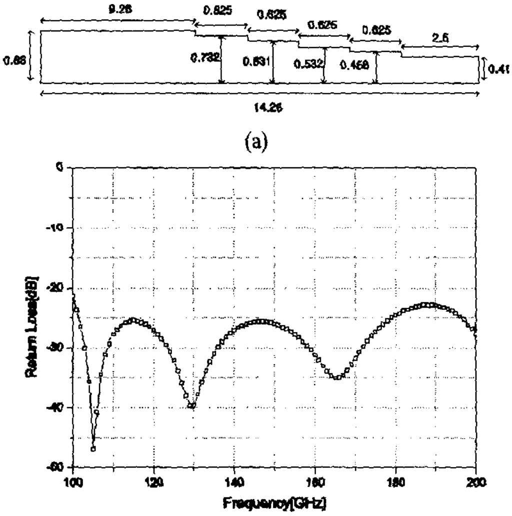


Fig. 3. Calculated return losses of the mixer mount (gap distance: square −15 μm, triangle −25 μm, circle −35 μm).



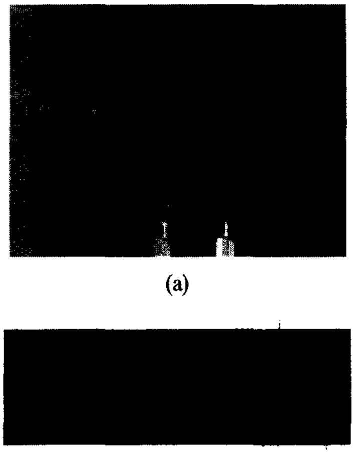
(a)

(b)

Fig. 4. (a) Designed stepped waveguide impedance transformer(unit: mm), (b) Calculated return loss.

The designed mixer block contains a waveguide impedance transformer shown in Fig. 4 to minimize the signal loss due to the impedance mismatch between the input waveguide of the mixer block(1.65×0.83 mm) and the half-height waveguide mount(1.65×0.41 mm). The calculated return loss of the waveguide impedance transformer is below −22 dB over the desired frequency range.

The center frequency and instantaneous bandwidth of the SIS mixer's IF are 1.4 GHz and 400 MHz, respectively. The real part of IF output impedance of the SIS mixer is generally larger than the normal state resistance of the SIS junction[1]. As the IF output impe-



(a)

(b)

Fig. 5. (a) IF impedance transformer including DC bias circuit, (b) SIS chip mounted inside the mixer block.

dance is a function of LO power, bias voltage and LO frequency, this value is assumed to be roughly two or three times the normal state resistance of the SIS chip[8]. Since the input impedance of the IF chain is normally 50 Ω, an IF impedance transformer is required to decrease the IF signal loss. Fig. 5(a) shows DC bias and the IF matching circuit which contains a two-section Chebyshev transformer fabricated from Rogers TMM6 ($\varepsilon_r = 6.0$). Aluminum wires(25 μm diameter) bonded to one end of the low pass filter of the SIS chip connects the SIS mixer to the IF matching circuit which also functions as a DC bias circuit. Ground connection to the SIS chip is made by filling the electrode of the SIS chip inside the channel across the waveguide section with indium.

Ⅲ. Measurement Results

Fig. 6 illustrates the developed SIS mixer over the frequency range 120 to 180 GHz. The SIS mixer block is machined from OFHC(Oxygen-Free High Conductivity) copper.

Fig. 6. Photograph of the developed SIS mixer.

Receiver noise temperature measurements were made using Y-factor method with room temperature(300 K) and liquid nitrogen(80 K) cooled loads. The relationship between the receiver noise temperature(T_{rx}) and the receiver's noise figure(F) is F=10 $\log_{10}(1+T_{rx}/300)$. For Nb(Niobium) based SIS mixers to operate, it is required to cool the SIS mixers to about 4 K. A closed-cycle refrigerator is utilized for the cryogenic cooling.

Fig. 7 describes a test receiver system for the noise temperature measurement. The LO chain consists of a Gunn oscillator(Nitsuki) followed by a frequency doubler(Radiometer Physics). The noise temperature and gain of the cooled HEMT IF amplifier are below 4 K and larger than 40 dB respectively across the IF frequency range 1.2 to 1.6 GHz. The cryogenic isolator is located between the output port of IF impedance transformer and the input port of the cooled HEMT IF amplifier. The receiver noise temperature(T_{rx}) referred to its input is represented as

$$T_{rx} = T_{RF} + L_{input} T_{mixer} + \frac{L_{input} T_{IF}}{G_{mixer}} \tag{1}$$

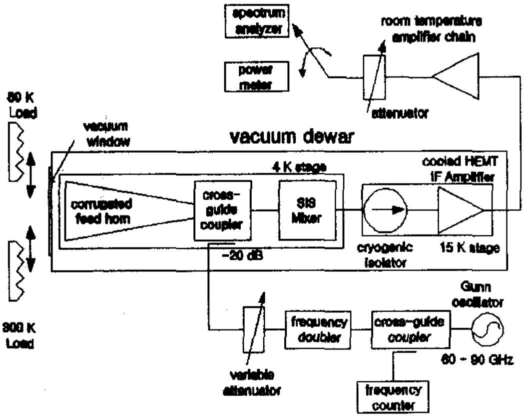


Fig. 7. Block diagram of the receiver system for the noise temperature measurement.

where T_{RF} is the noise caused by the RF input losses, L_{input} is the signal transmission loss due to the input optics like feed horn and cross-guide coupler, T_{mixer} is the SIS mixer noise temperature, G_{mixer} is the SIS mixer conversion gain, and T_{IF} is the noise temperature of the IF amplifier chain. The input noise added by the input RF optics can be determined using the method of intersecting lines[10] and this noise contribution is generally the largest portion in the overall receiver noise temperature at millimeter and submillimeter wavelengths. With the Y-factor method only the overall receiver noise temperature(T_{rx}) can be measured, which is the sum of each noise contribution. Fig. 8 shows LO pumped current-voltage curve and heterodyne response of the developed SIS mixer at 152 GHz using cold(80 K) and hot(300 K) loads. The measured DSB receiver noise temperature and conversion gain of the SIS receiver as a function of LO frequency are shown in Fig. 9. The conversion gain of the SIS receiver can be deduced from the DC I-V curve of the SIS junctions and IF power curve as mentioned in [11]. It was found that the receiver noise temperatures are higher in the frequency range 120～132 GHz. This is assumed to be caused by poorer return losses over that frequency range and not using of the inductive tuning circuit to compensate the SIS junction's geometric capacitance. The lowest noise temperature of the SIS receiver measured in this paper is about 32 K at 160 GHz. For reference, one of the lowest SIS receiver noise temperatures published to date is around 20 K(equivalent to three times the quantum noise).

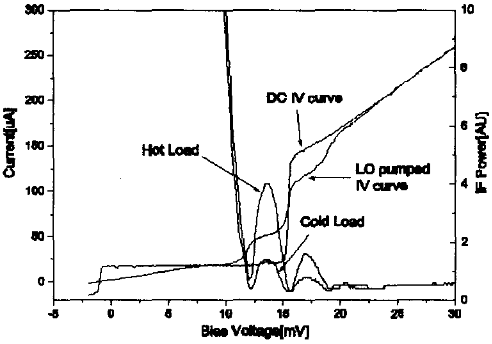


Fig. 8. LO pumped current-voltage and IF power curves for cold and hot loads at 152 GHz.

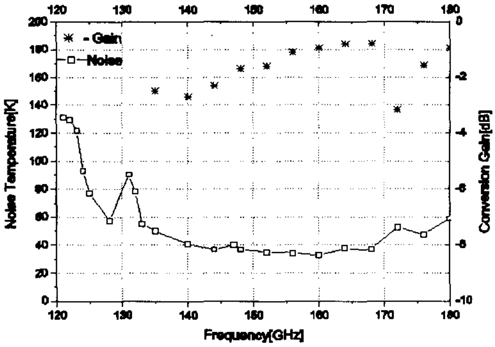


Fig. 9. Measured DSB receiver noise temperature and estimated conversion gain of the SIS receiver.

Ⅳ. Conclusions

We developed the SIS mixer over the frequency range 120～180 GHz with the design center frequency of 150 GHz. Even though the access to the SIS chip design and fabrication was not available at the time of development of the SIS mixer, a reasonably good noise temperature performance of the SIS receiver over the target frequency band could be obtained and it is acceptable for radio astronomical observations. In addition, the performance of the SIS mixer can be improved if the SIS chip design is incorporated into the development phase of the mixer block.

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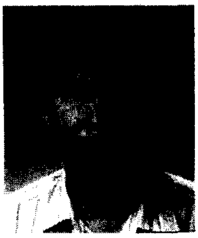

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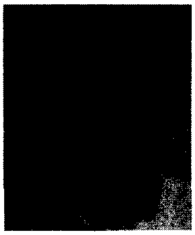

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