Development of Submillimeter-Wave SIS Mixers and ALMA Receivers

史生才1, 関本裕太郎2
1中国科学院紫金山天文台毫米波亚毫米波实验窒
2自然科学研究機構 国立天文台 先端技術センター

Sheng-Cai SHI1 and Yutaro SEKIMOTO2
1Millimeter- and Submillimeter-Wave Laboratory, Purple Mountain Observatory, CAS, China
2Advanced Technology Center, National Astronomical Observatory of Japan, NINS, Japan

Abstract: The submillimeter regime (100 to 1000 μm) is an interesting frequency window to be fully explored in astronomy. Observing astronomical spectral lines in this frequency regime is one of major scientific goals for the Atacama Large Millimeter/Submillimeter Array (ALMA), which will offer unprecedented angular resolution and sensitivity. With nearly quantum-limited sensitivity at millimeter and submillimeter wavelengths, superconductor-insulator-superconductor (SIS) heterodyne mixers enable the ALMA to achieve its performance. In this paper we mainly describe the design, simulation and characterization of submillimeter SIS mixers and the performance of the SIS receivers for ALMA bands 4, 8 and 10.

Key Words: submillimeter-wave, superconductor-insulator-superconductor (SIS), mixers, Atacama Large Millimeter/Submillimeter Array (ALMA), astronomy

1. Introduction

There are plenty of rotational molecular spectral lines and fine structure atomic lines observed in giant molecular clouds of gas and dust (interstellar medium) or in planetary atmospheres, which appear mostly in the submillimeter-wave regime (i.e., the shortest radio wavelengths and part of far-infrared, with a wavelength coverage of 100 – 1000 μm). They are very important tracers for studying the dynamics of astronomical objects such as stars and planetary systems. The Atacama Large Millimeter/Submillimeter Array (ALMA) project1 under construction will observe them with unprecedented angular resolution and sensitivity.

There are two different methods for detecting submillimeter spectral lines; heterodyne mixing2 and a broad-band spectrometry such as Fourier transform spectrometer (FTS)3. The former method incorporates a phase-locked local-oscillator (LO) signal to provide frequency resolution (∆ν) as high as 10⁶, whereas the latter has multiplex advantage but much lower resolution (<10⁸). Hence heterodyne mixers are widely adopted for observing submillimeter spectral lines with high frequency resolution. As mixers measure both amplitude and phase (i.e., coherent detection), which indeed cannot be known to arbitrary precision, there is a quantum limit (hν/2k_b, where h, ν, and k_b are the Planck constant, frequency, and the Boltzmann constant) in terms of Heisenberg’s uncertainty principle.

Compared with semiconductor ones, superconducting mixers have high conversion efficiency, nearly quantum-limited sensitivity, and significantly low LO power requirement. Low LO power requirement is especially beneficial to the development of heterodyne mixers in this particular frequency regime: submillimeter LO sources (solid-state ones in particular) usually have limited power. Here we introduce the development of submillimeter superconductor-insulator-superconductor (SIS) mixers4 and the receivers developed for the ALMA project.

2. Submillimeter SIS Mixers

Unlike infrared detectors, which absorb electromagnetic radiation directly through an electrode, submillimeter-wave mixers detect electromagnetic radiation through an antenna. The antenna can be either a planar quasi-optical one (such as a twin-slot and a spiral antenna, lithographically fabricated together with the mixing device) or a
waveguide feed (such as a corrugated horn and a diagonal horn). Waveguide feeds have much better beam characteristics than quasi-optical planar antennas, thus giving higher accuracy for astronomical observations. It is the reason that ALMA mixers all adopt waveguide feed horns. Fig. 1 shows an SIS mixer developed for ALMA band 10, with a diagonal waveguide feed horn included. The feed horn couples both the RF signal and the LO signal to be introduced into the mixing device.

Fig. 1 Photo (outside and inside view) of an SIS mixer for ALMA band 10.

Designing SIS mixers usually starts from the determination of the parameters of the mixing device (i.e., SIS junction). We firstly select the junction’s area ($A$) and the critical current density ($J_c$). These two parameters determine the junction’s normal-state resistance ($R_n$) and the mixer’s operation bandwidth (proportional to $J_c$). Here, the $J_cR_n$ product is a constant proportional to the junction gap voltage $V_{gf}$. In fact, the two parameters are chosen as a tradeoff between the desired mixer performance and the junction fabrication capability. A small junction area (large $R_n$) favors the impedance matching between the waveguide feed and the SIS junction, but not the fabrication of junctions. Similarly, the higher the $J_c$ is, the larger the junction’s leakage current becomes due to increased difficulty in fabricating perfect SIS junctions. Large leakage current will reduce the mixer conversion efficiency and increase the shot noise, which is indeed the dominant noise in SIS mixers. Hence, choosing a moderate $J_c$ (5–7 kA/cm$^2$, for example, for widely used Nb junctions) will lead to reasonably good overall performance for the mixer.

Since the junction’s RF impedance is approximately equal to $R_n e$, one may simply design the antenna (or waveguide feed) and its associated impedance transformer for the purpose of matching this impedance to the free-space impedance. For a broadband design, we usually simulate the junction’s mixing behavior (mainly conversion efficiency and noise temperature) for different impedance terminations at RF frequency sidebands, namely the upper and lower sideband (USB and LSB). Note that for submillimeter mixers, the two sidebands are pretty close and their harmonics can be neglected owing to considerable junction capacitance (short circuiting). Fig. 2 plots a simulation result at 500 GHz based on the quantum theory of mixing for a single Nb SIS junction (with $J_c=7$ kA/cm$^2$). Obviously, the optimum RF impedances (normalized resistance and susceptance) at this frequency can be found in terms of noise temperature and conversion efficiency, respectively. They may not coincide, just as shown in Fig. 2. The noise temperature becomes a good measure for evaluating the optimum RF impedance in this case.

Fig. 2 Simulated mixer performance (image: noise temperature, line: conversion gain) as functions of normalized RF resistance and susceptance.

A specific electromagnetic structure for the antenna (or waveguide feed) and its associated impedance transformer is simulated to meet the optimum RF impedance in the bandwidth of interest. Fig. 3 demonstrates an E-field (Electric field) distribution inside a submillimeter waveguide mixer mount. The transmission mode is the regular TE$_{10}$ mode inside the waveguide, but may change considerably inside the junction chip. By combining the simulated RF impedance with the junction’s circuit (discussed in the next section), we finally optimize the mixer’s overall performance.

Fig. 3 E-field distributed inside a waveguide mixer mount.

For submillimeter mixers, the RF and LO impedances seen toward the antenna (or waveguide feed) are approximately the same as the RF and LO frequencies are pretty close. Those seen toward the SIS junction, however, may differ to some extent as the levels of the RF and LO signal across the SIS junction are rather different (small vs. large signal). The
intermediate-frequency (IF, beat frequency between RF and LO) output impedance of the SIS junction is approximately equal to the junction’s dynamic resistance. It may have a considerable capacitance resulting from the junction circuit, which limits the mixer’s IF bandwidth.

There are two kinds of tunneling effects in SIS junctions, i.e., Cooper-pair tunneling (Josephson effect) and quasi-particle tunneling. The latter is responsible for SIS mixers, but the interference between the two effects increases with frequency. Applying a magnetic field to the junction barrier can suppress the Josephson effect. SIS junctions of a diamond-like shape, which are commonly adopted in incoherent detectors, may help reduce the fluctuation of the junction’s critical current against magnetic field.

3. SIS Junctions and Integrated Tuning Circuitry

The SIS mixer circuit, with the antenna (or waveguide feed) circuit as its input termination, consists of one or a few SIS junctions and integrated tuning and impedance transforming circuits. Those are based upon thin-film superconducting (or partly metallic) microstrip lines. They are characterized by combining the classical transmission line theory and Mattis-Bardeen theory addressing the complex conductivity of superconducting films.

The SIS junctions and integrated tuning circuit make up a resonance circuit that tunes out the junction’s geometric capacitance, while the impedance transforming circuit is introduced only when the impedance transformer included in the antenna circuit is insufficient. There are three kinds of integrated tuning circuits, i.e., shunted inductance (in parallel to SIS), end-loaded inductance (in series with SIS), and twin junctions (connected in parallel via an inductance). The third type, as shown in Fig. 4, is adopted for the SIS mixers developed for ALMA bands 4, 8, and 10.

Fig. 4 Photo of an SIS mixer chip with twin-junction tuning circuit. Two identical SIS junctions are connected in parallel through a tuning inductive line. A quarter-wavelength impedance transformer is located just before the resonance circuit.

In principle, SIS junctions can work up to a frequency twice its gap frequency (i.e., $2f_{gap}=2eV_{gap}/h=4\Delta f$, with $2\Delta$ as the superconductor’s energy gap), which is about 1.4 THz for conventional Nb/AlOx/Nb junctions. Thin-film superconducting transmission lines, however, have a considerable propagation loss at frequencies beyond $f_{gap}$ since energetic photons break Cooper pairs in superconducting films. To make full use of the junction’s frequency limit, we need to incorporate superconducting films of larger $f_{gap}$ (e.g., NbTiN) or even metallic films (e.g., Al), which are indeed of less frequency dispersion. The SIS mixers for ALMA bands 4 and 8 (well below 700 GHz) both adopt full Nb technology, while that for ALMA band 10 (beyond 700 GHz) combines Nb SIS junctions and an integrated NbTiN/SiO$_2$/Al tuning circuit.

4. ALMA Receivers

ALMA receivers are split into ten bands covering the frequency range of 31.3–950 GHz. Except for band 1 (31.3–45 GHz) and band 2 (67–90 GHz), other bands are developed with waveguide SIS mixers. Bands 3–8 adopt sideband separating SIS mixers (called “2SB mixers”, and the USB and LSB are detected separately) with an IF bandwidth of 4–8 GHz, while bands 9–10 conventional double-sideband SIS mixers (called “DSB mixers”, and the USB and LSB are detected together without separating each signal) with an IF bandwidth of 4–12 GHz. Note that all the SIS mixers are required to be fixed-tuned, i.e., with no mechanical tuners. The National Astronomical Observatory of Japan leads the receiver development for ALMA bands 4, 8 and 10, in collaboration with Purple Mountain Observatory (bands 8 and 10), Osaka Prefecture University (bands 4 and 10), National Institute of Information and Communications Technology (band 10), and Academia Sinica Institute of Astronomy & Astrophysics (band 10).

Astronomical spectral-line observations with a 2SB receiver increase the sensitivity by reducing the atmospheric noise from the image sideband, and improve the calibration accuracy by detecting the two sidebands separately. It can also improve the sensitivity for continuum-emission observations since the IF bandwidth is doubled. The 2SB mixers for bands 4 and 8 are both developed by adopting the same scheme as microwave image-rejection mixers. As shown in Fig. 5, a 2SB mixer consists of the following components; (i) two identical DSB SIS mixers, (ii) a 3-dB RF quadrature hybrid coupler that splits the RF signal in two equally but with a 90-deg phase difference, (iii) an in-phase 2-way equal power divider for the LO signal, (iv) two -17 dB couplers combining the RF and LO signals before being coupled to the two DSB SIS mixers, and (v) a 3-dB IF quadrature hybrid coupler combining the IF signals down-converted in
both mixers. Such a scheme will separate the detected USB and LSB signal. The image rejection ratio (separation capability) is required to be better than -10 dB for ALMA 2SB receivers. For this requirement the phase and amplitude imbalance are indeed not very critical. For example, a 3-dB amplitude imbalance and 30-deg phase imbalance would lead to -10dB image rejection.

![RF quadrature hybrid coupler and LO signal diagram](image)

**Fig. 5** Photo of a 3-dB RF quadrature hybrid coupler and an in-phase 2-way power divider for the LO signal.

Fig. 6 summarizes the receiver noise temperatures measured at a bath temperature about 4 K, for band 4, 8 and 10 SIS mixers. Note that band 4 and 8 SIS mixers are measured in SSB mode (almost doubling that in DSB mode) and band 10 in DSB mode. It is clearly seen from Fig. 6 that both the noise temperature and the bandwidth of the three SIS mixers meet the ALMA specifications.

![Noise temperature vs. frequency graph](image)

**Fig. 6** Measured receiver noise temperatures for band 4, 8 and 10 SIS mixers, with bands 4 and 8 in SSB and band 10 in DSB.

5. Summary

The design, simulation and characterization of submillimeter SIS mixers have been thoroughly described. With a fixed-tuned design, the SIS mixers developed for ALMA band 4, 8 and 10 all demonstrate high sensitivity in a large bandwidth, meeting the ALMA requirements.

Acknowledgment

The authors would like to acknowledge the contributions of Y. Uzawa, S. Asayama, T. Noguchi, J. Inatani, ALMA Front End IPT, NAOJ-ATC, SIS, Band 4, 8 and 10 groups, mechanical engineering shop, and ALMA-J office at NAOJ and its collaborators at PMO, Osaka Prefecture University, NiCT, and ASIAA. S.C. Shi is supported by NSFC under Grant No. 1062103.

References

1) The ALMA project, see http://www.almaobservatory.org/
7) High frequency structure simulator, Ansoft, LLC, Suite 200, Pittsburgh, PA 15219.

□著者紹介□

**Sheng-Gai Shi**

Born in 1965  
Educational background:  
Professional experience:  
Research background:  
Development and applications of THz superconducting detectors  
E-mail: nshi@mail.astro.ac.cn

**Yutaro Sekimoto**

Educational background:  
1994 PhD University of Tokyo  
Professional experience:  
Research background:  
Submillimeter-wave Astronomy, Submillimeter-wave instrumentation  
Astronomical Society of Japan, Physical Society of Japan, International Astronomical Union  
E-mail: sekimoto.yutaro@nao.ac.jp