Development of a 275-500 GHz waveguide SIS mixer and dual band LO injection system

T. Kojima*[1], M. Kroug[1], A. Gonzalez[1], K. Uemizu[1], K. Kaneko[1], A. Miyachi[1], Y. Kozuki[2], S. Asayama[1]
[1] National Astronomical Observatory of Japan, Mitaka, 181-8588, Japan
[2]Osaka Prefecture University, Sakai, 599-8531, Japan
*Contact: t.kojima@nao.ac.jp

Abstract— **In this paper, we report on the design and performance of a prototype SIS mixer covering ALMA band-7 (275-373 GHz) and band-8 (385-500 GHz). The waveguide SIS mixer is based on a parallel connected twin-junction circuit with a current density of about 25 kA/cm^2. For the DSB mixer evaluation system, a wideband corrugated horn antenna and a 15-dB RF/LO coupler have been designed and fabricated. LO sources for such a broad frequency coverage are currently not available, therefore, a dual band LO injection system with two LO sources and an LO diplexer have been used. The measured DSB receiver noise temperature ranges from 45 to 90 K and is compliant with existing ALMA band 7 and 8 receiver noise temperature specifications.**

I. Introduction

At NAOJ, we are developing wideband sub-mm SIS mixers based on high-current-density junctions to cover two ALMA bands with the same receiver. In order to benefit from all equipment and know-how acquired during the design and production of ALMA band 8 receivers, we are aiming to cover ALMA band 7 (275-373 GHz) and band 8 (385-500 GHz) simultaneously. The fractional bandwidth of this target band is slightly over 60%. An increase in RF bandwidth of ALMA receivers can lead to the reduction of the total number of receivers to be operated and maintained in the ALMA front end, which would make operations more effective and increase the time devoted to science observations. In addition, the wider spectral range coverage with the same receiver and LO calibrations offers the possibility of new observation modes as described for example in the ALMA band 2+3 science case [1].

The development of a heterodyne receiver with large fractional bandwidths poses technical challenges for most components such as the SIS mixers, local oscillator source and waveguide parts including a corrugated horn and RF/LO coupler. In particular, high critical current density (J_C) junctions yielding low RC products are essential to achieve wide RF band performance [2]-[4]. Moreover, performance of the wideband receiver should not be compromised even if the frequency coverage increases. For example, we should keep the quantum-limited noise performance, and comply with ALMA specifications for both bands 7 and 8 to perform scientific observations in the same level as the current one.

In this paper, we describe the design and performance of the first prototype of a wideband waveguide SIS mixer and evaluation system covering the frequency range from 275 GHz to 500 GHz.

II. Band 7+8 SIS mixer design

Our mixer block is similar to the one described in [5]. The mixer block consists of three parts, a main body implementing a waveguide and chip slot, a back piece with the backshort, and an IF module with a 50-Ω microstrip line and a coaxial connector. The SIS mixer chip with dimensions 60 μm×180 μm× 2.2 mm is suspended over the chip slot, and is fixed at both ends with glue as shown in Fig. 1. The mixer chip is designed to cover the very wide RF bandwidth and comprises a waveguide probe in combination with a WR-2.3 (290 μm x 580 μm) waveguide, matching circuits employing high current density junctions, and IF output circuitry incorporating a low pass filter and an IF pad to connect an IF 50 Ω line with bonding wires.

We designed an asymmetric single-side waveguide probe placed across the reduced-height waveguide with dimensions 100 μm x 580 μm. The shape of the waveguide probe was empirically optimized to have nearly constant impedance in the desired RF range. Fig 2 (a) shows the simulation result of the probe impedance. The simulated probe impedance was around 30 Ω and slightly capacitive.

A scanning electron microscope image of the RF matching circuit is shown in Fig.1. The circuit comprises an $Nb/SiO_2/Nb$ microstrip line and parallel-connected $Nb/AlN_x/Nb$ twin junctions and is designed for a current density of around 25 kA/cm^2. The nominal junction diameters are ϕ =0.9 μm. The matching circuit implements a single-section quarter-wave impedance transformer to obtain the wideband performance. Fig. 2 (b) shows the calculated power coupling between feed point of the probe to the SIS junctions. The calculation was performed on the basis of the equivalent circuit shown in the graph in Fig. 2 (b). The design was optimized to maximize the coupling and the bandwidth. The calculated coupling is typically more than 90 % or return loss more than 10 dB. However, the coupling at the lower band edge gets deteriorated. SIS mixers with an updated design applying a multi-section impedance transformer with improved bandwidth coverage will be included in a future publication.

III. Band 7 and 8 Dual band evaluation system

Fig. 3 shows our DSB noise temperature measurement system and is similar to of the one described in [5], which focused on the wide IF bandwidth performance of a mixer-

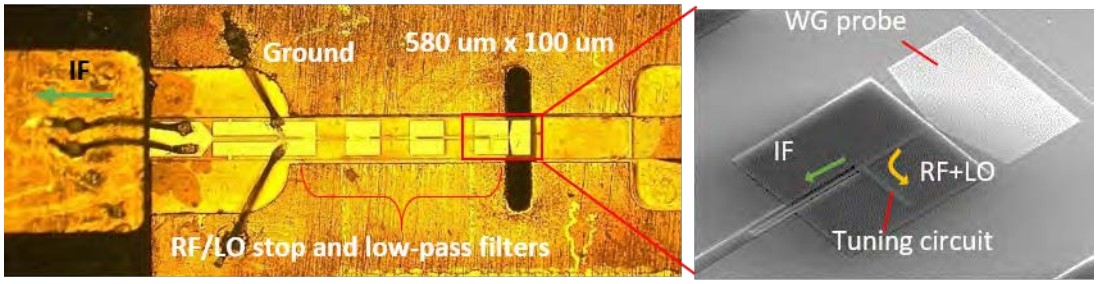

Fig. 1. Optical photograph of the SIS mixer chip mounted on the mixer block and scanning electron microscope image focusing on the waveguide probe and mixer matching circuit.

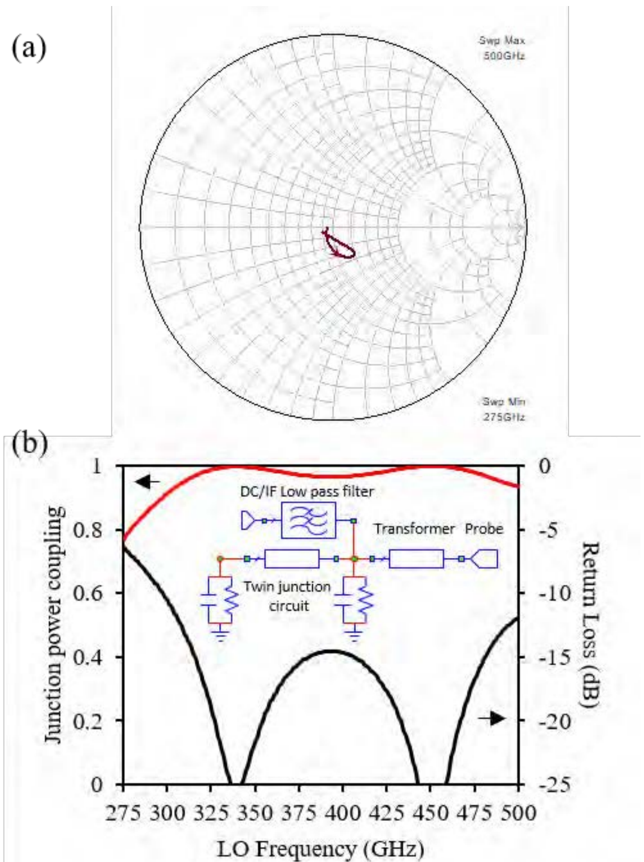

Fig. 2. (a) Simulation result of the designed probe impedance over 275-500 GHz. The Smith chart is normalized to 30 Ω. (b) The calculated junction power coupling and return loss of the designed matching circuit. The calculation is based on the equivalent circuit shown on the graph.

preamplifier module at ALMA band 8 frequencies (385-500 GHz). We modified this system and expanded the RF range to include ALMA band 7 frequencies (275-373 GHz).

On the RF side, the cryostat implements a 12.5-µm-thick polyimide film as a vacuum window and an infrared filter. The reflection loss of the polyimide film has been measured by terahertz time domain spectroscopy and is less than 3 % over the band 7 and 8 frequencies. A corrugated horn antenna [6] attached to a 15-dB RF/LO waveguide coupler, and the SIS mixer block are located on the 10 K stage. The corrugated horn antenna has a profiled shape to achieve the wideband performance in terms of return loss and cross polarization. The measured return loss is higher than 20 dB over the whole band. The RF/LO coupler, fabricated by direct machining, incorporates 3 slots with a 30-µm width between two parallel waveguides of 290 µm x 700 µm. The coupling of the RF/LO coupler ranges from −17 to −14 dB.

The target RF bandwidth is too wide for typical LO sources at these high frequencies, and therefore we applied a dual band LO system incorporating an LO diplexer [7]. The system allows us to evaluate an SIS mixer in one cooling cycle without any change of the configuration in the cryostat. The LO sources use ALMA band-7 and band-8 warm cartridge assemblies, which allow us to electrically control and generate high LO power with low amplitude noise [8], [9]. Cryogenic frequency multipliers x3 and x6 are located on the 10-K stage inside the cryostat and generate the final LO power in the frequency ranges of 283–365 GHz and 393–492 GHz. The frequency diplexer functions as the combiner of the two LO frequency bands. The output LO power from the diplexer is transmitted to the RF/LO coupler through a WR-4.3 oversized waveguide made of CuNi, and then is injected into the SIS mixer. The LO powers to pump SIS junctions are sufficient at the bands 7 and 8 frequencies. The IF chain in this study uses a cryogenic isolator and a cryogenic low-noise amplifier (CLNA) with a typical noise temperature of 2.1 K over the 4-8 GHz range [10]. Output IF power from the cryogenic IF chain is amplified with a room temperature amplifier and measured with a power meter and a spectrum analyzer.

IV. MEASUREMENT RESULT

We have fabricated two wafers with current densities $J_C \sim 26$ kA/cm^2 and $J_C \sim 60$ kA/cm^2, the latter unintentionally resulting in a current density much higher than the design value. The DSB noise temperature measurement was carried out by the standard *Y*-factor method using liquid-nitrogen cooled and room temperature blackbody loads. Preliminary measurement results for the DSB noise temperatures are 45 K to 90 K over the 283-492 GHz frequency range. Interestingly, both mixers showed similar performance even though their current densities differ by a factor of more than 2, indicating that the circuit design is very tolerant for a wide range of load impedances. The results fully comply with current ALMA band 7 and band 8 receiver noise temperature specifications. Note that the ALMA spec. is divided by 2 to translate from 2SB to DSB specification.

The updated second design of the SIS mixers, its performance and characterization are included in an extended

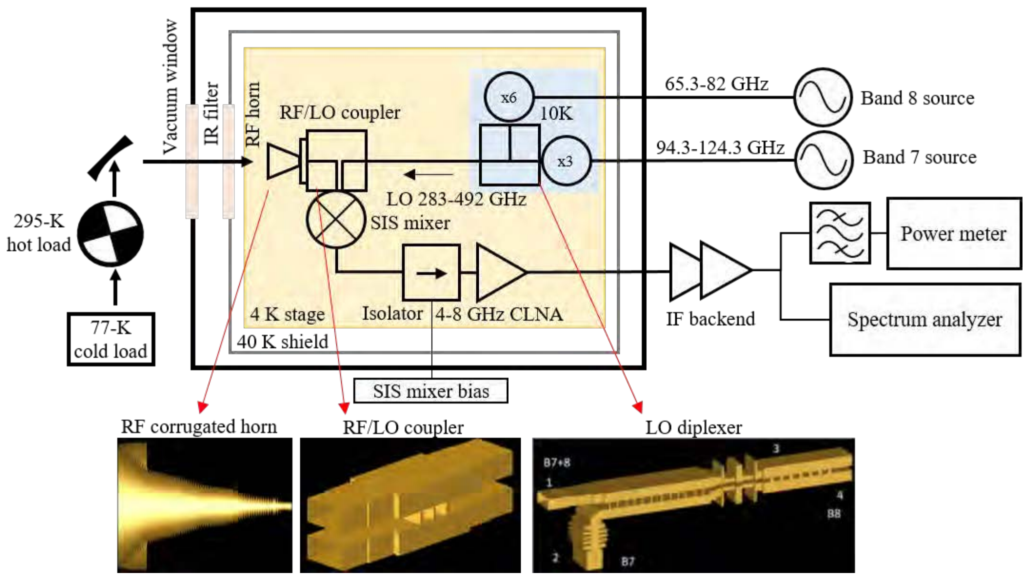

Fig. 3. Schematics of the noise temperature measurement setup with dual band LO injection system. The RF corrugated horn and the LO diplexer have been described in references [6] and [7].

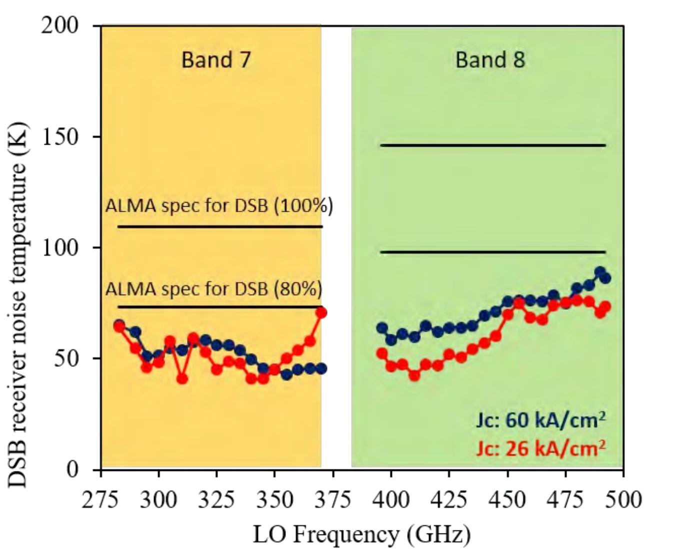

Fig. 4. Measurement results of the DSB receiver noise temperature for two SIS mixers with the critical current density of 26 and 60 kA/cm^2. The ALMA specs. at bands 7 and 8 are divided by 2 to translate from 2SB to DSB specification.

paper which has been submitted to IEEE Transactions on Terahertz Science and Technology.

Acknowledgment

The authors would like to thank Y. Uzawa, W. Shan, Y. Niizeki, S. Ezaki, and Y. Fujii in the NAOJ receiver development team for their support and helpful discussions.

This work was supported in part by JSPS KAKENHI Grant Numbers 15H02074.

References

[1] Fuller, G.A., et al., "The Science Case for ALMA Band 2 and Band 2+3", arXiv:1602.02414.

[2] H. W. Bode, Network Analysis and Feedback Amplifier Design, New York, NY, USA: Van Nostrand, 1945.

[3] R. M. Fano, "Theoretical limitations on the broadband matching of arbitrary impedances," Journal of the Franklin Institute, vol. 249 pp. 57–83, Jan. and pp. 139–154, Feb. 1950

[4] A. R. Kerr, "Some fundamental and practical limits on broadband matching to capacitive devices, and the implications for SIS mixer design," *IEEE Trans. Microw. Theory Techn.*, vol. 43, no. 1, pp. 2-13, Jan 1995.

[5] T. Kojima, M. Kroug, K. Uemizu, Y. Niizeki, H. Takahashi and Y. Uzawa, "Performance and Characterization of a Wide IF SIS-Mixer-Preamplifier Module Employing High-*Jc* SIS Junctions," *IEEE Trans. THz Sci. Technol.*, vol. 7, no. 6, pp. 694-703, Nov. 2017.

[6] A. Gonzalez, K. Kaneko, and S. Asayama, "Recent work on (Sub-)mm-wave ultra wideband corrugated horns for radio astronomy," 11th European Conference Antennas and Propagation (EuCAP), IEEE, 3327-3331 (2017)

[7] A. Gonzalez, T. Kojima, K. Kaneko, S. Asayama, "275-500 GHz Waveguide Diplexer to Combine Local Oscillators for Different Frequency Bands," *IEEE Trans. THz Sci. Technol.*, vol. 7, no.6, 669–676, Nov. 2017

[8] Y. Sekimoto, Y. Iizuka, N. Satou, T. Ito, K. Kumagai, M. Kamikura, M. Naruse, and W. L. Shan "Development of ALMA Band 8 (385-500 GHz) Cartridge", in *Proc. 19th Int. Symp. on Space THz Technol.*, Groningen, Netherlands, April 2008

[9] E. Bryerton and J. Hesler "Sideband noise screening of multiplier-based sub-millimeter LO chains using a WR-10 Schottky mixer", in *Proc. 19th Int. Symp. on Space THz Technol.*, Groningen, Netherlands, April 2008

[10] Low Noise Factory AB, G¨oteborg, Sweden. [Online]. Available: http://www.lownoisefactory.com/