A SIS Mixer for ALMA Band 10: Development Concept

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***Abstract*—Conceptual design of waveguide and quasioptical mixers for ALMA Band-10 is presented along with SIS chip performance estimates. A combination of NbTiN/Al tuning circuit with the Nb-based high current density SIS junctions employing AlN tunnel barrier ($A = 0.5\ \mu m^2$, $J_c = 15 - 20\ kA/cm^2$) is suggested as the base-line. The following parameters are expected for a 20-Ω SIS mixer: $G_m = -7.5 \ldots - 9$ dB, $T_m < 200$ K (DSB), $P_{LO} < 1\ \mu W$ at 950 GHz. Tunerless full-height waveguide (280 µm × 140 µm) mixer will employ a single-side chip probe-antenna configuration. A chip-package concept is under development for quick mounting (replacement) of serial mixers. Quasioptical mixers will be used for material research and as an option for a weak LO source. A quasioptical balanced mixer can reduce LO power requirement down to only 3-5 µW for the whole two-polarized cartridge along with essential simplification of its optical scheme. The IF range of 4-12 GHz is simulated successfully for the quasioptical mixers.**

***Index Terms*—Balanced mixer, quasioptical mixer, SIS mixer, slot antenna, SNAP process.**

I. INTRODUCTION

THE Band-10 (787 – 950 GHz) is currently the highest frequency range of Atacama Large Millimeter and Submillimeter Array (ALMA) [1], which employs the quantum-noise-limited SIS mixers [2]. The difficult point in designing the front-end mixer is that whole frequency range spreads far above the gap-frequency of Nb (≈ 700 GHz), so this material cannot be used for tuning circuit of a SIS junction; the use of normal metals or higher gap-frequency superconductors has to be considered [3]. To achieve the ALMA Band-10 specification for the receiver noise temperature in the double-side-band regime (DSB), $T_{RX} \leq 230$ for 80 % of the band and $T_{RX} \leq 345$ K for any point of the band [4], both the SIS junction technology and the materials for the tuning circuit must be selected very carefully.

There are not many choices for a beam launcher. The corrugated horn antenna is known for its high-quality beam properties. In spite of severe mechanical tolerances, which are about 10 µm, the feasibility of corrugated horn antennas is proven within 800-1000 GHz frequency range by a number of experiments (e.g. HIFI and ASTE projects) [5], [6]. The waveguide approach applies severe mechanical requirements also to the mixing chip: typical dimensions of the chip will be about $500 \times 50 \times 30\ \mu m^3$. This makes chips difficult to process/handle and may slow down the research phase of the project.

Another approach is the well-known integrated lens-antenna [7], [8]. Although the beam quality of known lens-antennas is not as good as for horn launchers, this direction is growing rapidly mainly due to much simpler mixer mechanics, shorter fabrication run and easier chip handling, while the receiver noise can be as low as for waveguide mixers. The analysis of an ideal corrugated feed estimated total sidelobes of the ALMA system antenna at ≈ 20 dB [9] that is just few dB lower than the sidelobes of a practicable elliptical silicon lens-antenna SIS mixer [8]. It means that the final (system) difference between the horn-antenna (waveguide) and the lens-antenna SIS mixers can be a marginal issue.

The output port capacitance of a SIS chip can be essential, so advanced electromagnetic design is needed for efficient coupling of the signal within intermediate frequency (IF) band of 4-12 GHz. A narrower IF band of 4-8 GHz is allowed in the case of single-side-band (SSB) operation. The tunerless method of the side-band separation is developed and tested for waveguides at millimeter wavelengths using two identical mixers and RF/IF 3-dB hybrid couplers [10]. However, this method seems difficult to implement, since not only very small mechanical tolerance is needed to balance the mixers, but also because of essential signal loss in a rectangular single-mode waveguide at terahertz frequencies.

Another difficult point is the submillimeter local oscillator (LO) compatible with the ALMA cartridge concept. Recent solid-sate tunerless sources based on chain multipliers are hardly able to deliver the LO power higher than 10-20 µW

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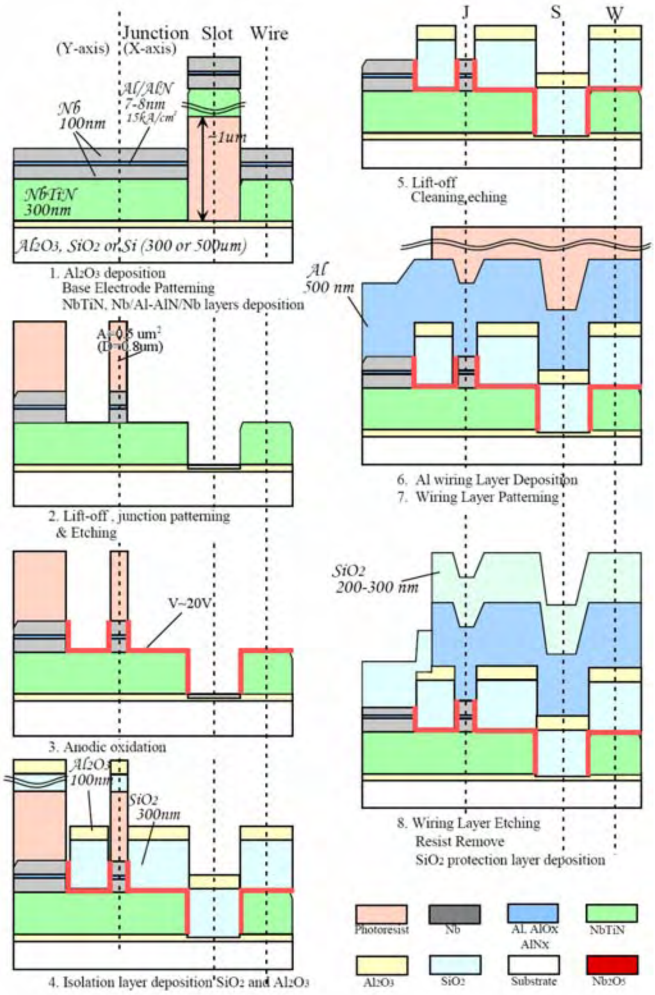

Fig. 1. SIS junction fabrication flow-charts for SNAP technique.

Fig. 2. The g-Line Stepper machine (top) and developed sub-micron photoresist patterns within one-shot exposing area of 3.5 x 3.5 mm^2 (bottom).

within the desired frequency range [11] that is not sufficient even for a state-of-the-art SIS mixer, if input beam-splitter is used. The LO powers of order of 200 µW are still a unique and narrow-band issue [12]. This is why the balanced SIS mixer approaches [13], [14] could be of great interest.

In present paper we discuss the development of the SIS mixer and the front-end optics for ALMA Band-10. Conceptual designs for waveguide and quasioptical mixers are presented along with SIS chip performance estimates.

II. APPROACHES AND DETAILS OF DESIGN

A. *SIS Junction Fabrication and Mixer Performance*

The ALMA 'mass production' has to account for assurance issues for SIS junctions and other components of the RF circuit. To easier achieve the specified (wide) RF frequency range, the Nb-based high current density submicron-size SIS junctions with AlN tunnel barrier [15] ($A = 0.5$ µm^2 or 0.8 µm diameter, $J_c = 15 - 20$ kA/cm^2) are being fabricated at NAOJ using SNAP technique (presented in Fig. 1) and the new 4-target RF/DC deposition plant (from Ulvac) along with the projection g-Line Stepper machine (shown in Fig. 2). Since the previous experimental results [16]-[19], the NbTiN/SiO$_2$/Al microstrip is accepted as the base-line for the tuning circuit. The electromagnetic simulation of the RF circuit demonstrated that the traditional Al_xO_y barrier SIS junctions ($A = 0.8$ µm^2 or 1 µm diameter, $J_c = 10 - 12$ kA/cm^2) can also suit the ALMA specifications. The calculations using Tucker's theory (3-port model includes the quantum reactance) [2] predict the following parameters for a 20-Ohm SIS mixer: $G_m = -7.5 \ldots -9$ dB (3-dB loss of the tuning circuit with RF sheet resistivity of 0.1 Ω/sq included), $T_{RX} < 200$ K (DSB) (for realistic value $T_{IF} < 10$ K) and $P_{LO} < 1$ µW at 950 GHz (no optics loss included). The example of simulation data is presented in Fig. 3.

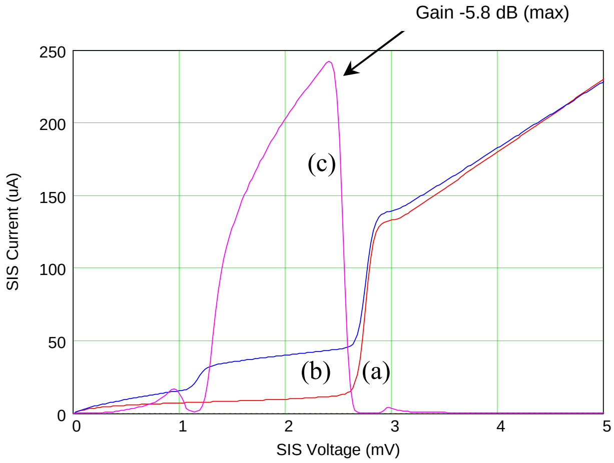

Fig. 3. Simulated IV-curves: un-pumped (a) and pumped (b). The simulated gain of SIS mixer at 950 GHz is presented by (c).

B. Waveguide Mixer

The suggested tunerless full-height waveguide (280 µm × 140 µm) mixer will employ a single-side probe-antenna [20] as shown in Fig. 4. The coplanar waveguide at the IF output facilitates the wide IF band: the RF chokes are grounded, so they do not contribute to the output capacitance. A chip-package concept (see Fig. 5) assumes a SIS junction staying within its particular waveguide mount (chip-package) for repeatable tests; there no need to dismount good chip for testing another one. The new chip can use its own package. Many mixers can be pre-certified at RF using the common parts of only one mixer block – the corrugated horn antenna and the fix-tuned backpiece.

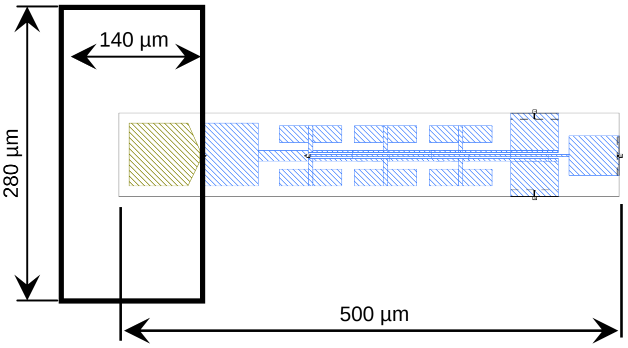

Fig. 4. Probe-antenna chip mounted in full-height waveguide (scheme).

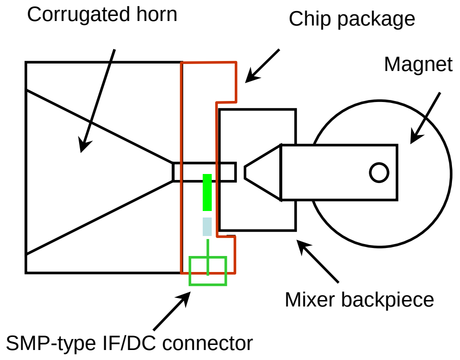

Fig. 5. Chip packaging concept for waveguide mixer.

C. Quasioptical Mixers

Since quasioptical chips are easier to process, and they can be handled with much less caution, the lens-antenna mixer can be used as a handy test platform for SIS junctions and tuning circuits (materials). It is worth to note that high-quality epitaxial films from NbN for terahertz-range applications [21] can be grown presumably on the high-dielectric MgO substrate (ε = 9.6), which are difficult to use with waveguides.

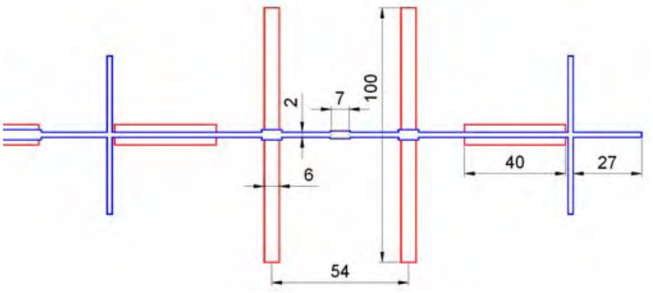

Fig. 6. Layout of quasioptical SIS mixer based on a double-slot antenna.

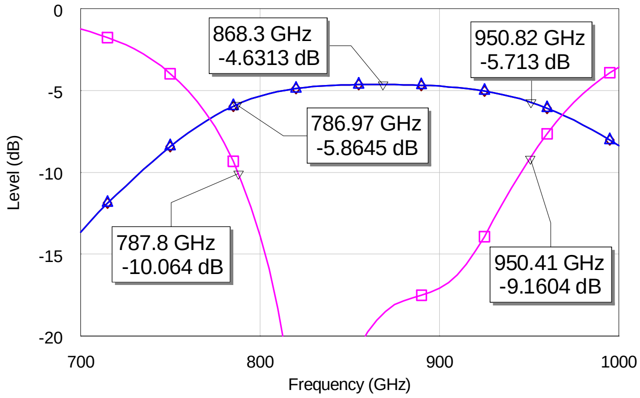

Fig. 7. Signal coupling (top curve) and reflection (bottom curve) for the QO mixer from Fig. 6 (simulation). The coupling level has to be corrected up for 3 dB, since two equal SIS junctions are used.

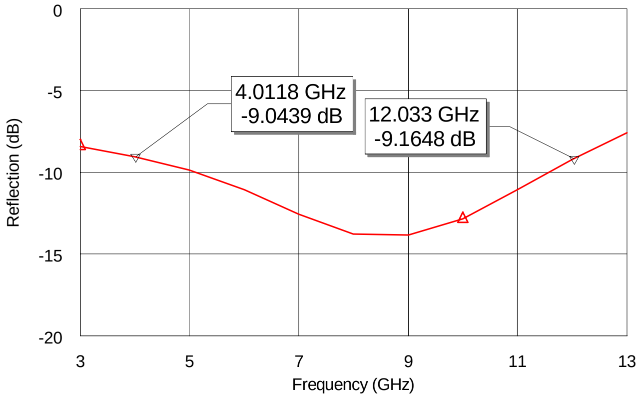

Fig. 8. Output port (IF signal) coupling to a 50-Ω load for the QO mixer from Fig. 6 (simulation).

We are going to use the quasi-optical mixing structure presented in Fig. 6 to facilitate the waveguide SIS mixer development. Simulations predict good performance of such mixer as shown in Fig. 7, which employs the twin-junction tuning circuit [22]-[24]. It is important to note that in spite of larger size of the chip (larger circuit), the IF range of 4-12 GHz is simulated successfully for the quasioptical mixers as shown in Fig. 8. However, this smooth figure seems realistic only in the case of the integrated IF amplifier [25].

A quasioptical balanced mixing structure (QBM) from Fig. 9 can be accepted as the main option in the case of weak LO. The new scheme of QBM is using two crossed double-slot antennas [13], which separate orthogonally polarized LO and signal. The LO power is injected symmetrically to the signal slot-antennas via integrated RF interface providing anti-phased IF signals at two twin-junction SIS mixers. We estimated essential reduction of LO power requirements down to only 2-3 µW for the whole two-polarized cartridge as presented in Table I.

The implementation of the balanced mixer allows for essential simplification of the optical scheme of the cartridge as presented in Fig. 10. It is important that the launching beam angle can be defined via proper design of the elliptical lens, which is the only non-flat optical element between the SIS mixer chip and the sub-reflector of the telescope.

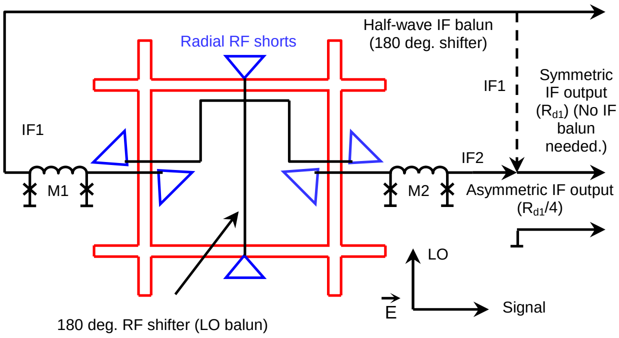

Fig. 9. Conceptual scheme of balanced quasioptical SIS mixer employing the crossed double-slot antenna and two twin-junction detectors. Polarizations for signal and local oscillator are shown at the bottom.

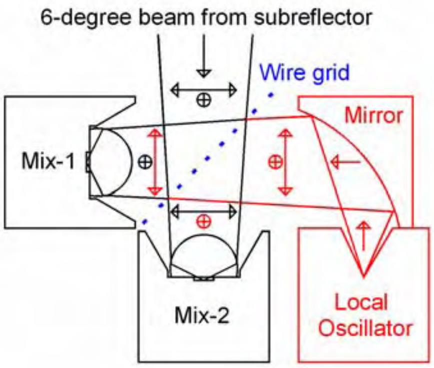

Fig. 10. Optical scheme of double-polarized receiver cartridge employing two balanced SIS mixers (Mix-1 and Mix-2) from Fig. 9 (simplified).

TABLE I

LO REQUIREMENTS FOR CARTRIDGE WITH BALANCED MIXERS

LO frequency (GHz)	RF Power before 3 dB loss (µW)	Coupled RF power (µW)	Mixer gain, Gm/after 3 dB loss (dB)	Optimum LO voltage (α_{RF}) (a.u.)	DSB T_{RX} (K)
780	1.9	0.8	-5 / -8	0.64	-
865	2.3	1.12	-5.2 / -8.2	0.70	-
950	2.8	1.28	-5.8 / -8.8	0.70	198

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