Development of Balanced SIS Mixers for ALMA Band-10

Sergey V. Shitov, Oleg V. Koryukin, Yoshinory Uzawa, Takashi Noguchi, Andrey V. Uvarov, Ilya A. Cohn

***Abstract*—A few concepts of a wide-band balanced SIS mixer employing submicron-sized SIS junctions are under development for 787-950 GHz frequency range. A quasioptical DSB balanced mixer with integrated cross-slot antenna is considered as the less laborious and cheaper option. The silicon lens-antenna beam efficiency is expected above 80 % across the whole band with first-order sidelobe below -16 dB.**

To use the conservative horn antenna solution, a single-chamber waveguide DSB balanced mixer is developed. Two equal probe-type SIS chips are inserted into a full-height waveguide through its opposite broad walls; these two mixers are driven by the signal waveguide in series. The LO current is transferred to the mixers in parallel via a capacitive probe inserted through the narrow wall of the signal waveguide from the neighboring LO waveguide. The HFSS model demonstrated the LO power coupling efficiency above -3 dB, almost perfect signal transfer and the LO cross talk below -30 dB that take into account misalignment (misbalance) of the chips.

It is demonstrated numerically using Tucker's 3-port model that unequal pump of junctions of a twin-SIS mixer can lead, in spite of the perfect signal coupling, to degradation of the gain performance up to -3 dB, especially at the top of the ALMA Band-10.

***Index Terms*—SIS mixer, balanced mixer, lens antenna.**

I. INTRODUCTION

The LO power required for a THz-band SIS mixer can be below 1 μW. However, the simple LO coupling circuit, which uses a thin-film beam splitter, wastes usually more than 90% of the available LO power into a termination load. The commercially available wide-band tunerless LO sources [1] can presently provide only few microwatts in the THz range. To reduce the LO power requirements, a balanced mixer is that possible solution. One may estimate the figure down to only 2-3 μW for a two-polarized SIS receiver, if submicron SIS junctions are used in the balanced mixer configuration.

There are a few options for waveguide balanced and side-band separating mixers employing the straightforward connection of the DSB mixers using hybrid couplers [2]. However, the low-loss operation of the waveguide-based connections and the required balancing of the mixers both are of a great concern in the THz frequency range. This is a good reason to look for the more compact design of the RF circuit for waveguide or/and consider an integrated quasioptical SIS mixer design.

It is known that the conversion gain of a SIS junction is reducing essentially above the gap frequency, and it turns negligibly low above twice the gap frequency. The ALMA Band-10 DSB receiver specification for T_{RX} is 230 K within 80% of the band 787-950 GHz and 345 K at any frequency of the band. The IF range of 4-12 GHz is required for the DSB receiver with ripples below 4 dB within each 2 GHz segment. All these make the accurate design of the mixer's RF and IF circuits very important.

Since the Q-factor of a SIS junction at submillimeter wavelength is high (Q>>1), the twin-SIS junction [3]-[5] is a good solution providing about twice RF bandwidth of a single junction. However, it is known that two junctions in the twin-SIS are unequally coupled at RF across the band, thus providing less gain than one can expect from the equivalent junction of the same R_n. This effect is difficult to estimate experimentally, since two junctions are connected in parallel at DC. The growing importance of such accurate analysis in THz range can be motivated with concern of the essential drop of conversion gain of a Nb-based SIS mixer closer to 1 THz. To analyze the effect of unequal pump and dynamic resistance for a two-junction SIS mixer, the Tucker's 3-port model can be used yet being expanded to multi-junction mixing arrays.

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II. BALANCED MIXER DESIGN

A. Quasioptical SIS mixer

A few concepts of a wide-band balanced SIS mixer employing submicron-sized SIS junctions (A = 0.5 sq.μm) are under development at NAOJ for ALMA Band-10. Considering a general THz-range SIS mixer, the quasioptical (QO) lens-antenna approach seems less laborious, that is confirmed experimentally [6]. Quasioptical chips are easier to process, and they can be handled with much less caution. It is worth to add here that high-quality epitaxial films of NbN [7], which is a promising option for a

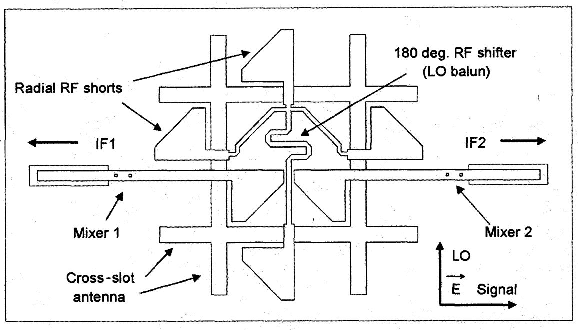

Fig. 1. Layout of quasi-optical balanced SIS mixer chip for use with silicon immersion lens. The outer rectangle presents ground plane (metallization) of slot-antenna circuit.

low-loss tuning circuit, can be grown presumably on MgO high-dielectric ($\varepsilon = 9.6$) substrate, that is difficult to use with waveguides. The simplified layout of the QO balanced mixer is presented in Fig. 1. The mixer employs two double-slot antennas, which are crossing each other in the areas of minimum RF current [8], thus minimizing both cross-talk and beam distortion. These two antennas are able to receive separately two orthogonal polarizations, one for LO and another for signal. The signal is coupled from vertical slots into the two twin-SIS mixers, Mixer 1 and Mixer 2. The LO power is first combined from two horizontal slots using a stripline 180-degree RF shifter (LO balun); then it is spitted in half and injected to the signal slots exciting them in *anti-phase* in respect to the phase of the signal. This prevents emissions of LO power in the direction of the signal beam, and the low signal-to-LO coupling can be achieved. Since the wide IF band (4-12 GHz), it is difficult to combine the anti-phased IF signals, IF 1 and IF 2 using a distributed 180-degree balun circuit (hybrid coupler). A series IF connection or an opposite polarity of the dc bias of the mixers [2] are that practicable solutions. Note that present design uses only two twin-SIS mixers, but not four as in [6]. Simulation predicts a wide-band RF performance of such mixer employing a parallel-feed tuning circuit; the IF range of 4-12 GHz is expected. However, such wide-band IF performance of the full receiver may need an IF amplifier integrated with the mixer block similar to [9].

The beam quality is the main concern of the quasioptical lens-antenna mixers. A few groups [10], [11] have carefully simulated the silicon lens-antenna. In spite its beam efficiency at the secondary reflector is not as good as for corrugated horns, we may expect the figure above 80 % across the whole ALMA Band-10 (for -10 dB taper at the subreflector). The lens-antenna sidelobes are the result of truncation of the printed antenna beam inside the lens due to the effect of full internal reflection. This makes the first-order sidelobes typically at -16 dB. The beam-width of a diffraction-limited lens-antenna is known to be defined by the diameter of the lens. This advantageous feature allows removing the intervening optics (ellipsoidal mirrors). The Gaussian impurity of the beam does not play now important role making resulting (system) beam nearly the same as for high-quality corrugated horn. The optical system of the cartridge with QO balanced mixers is presented in Fig. 2.

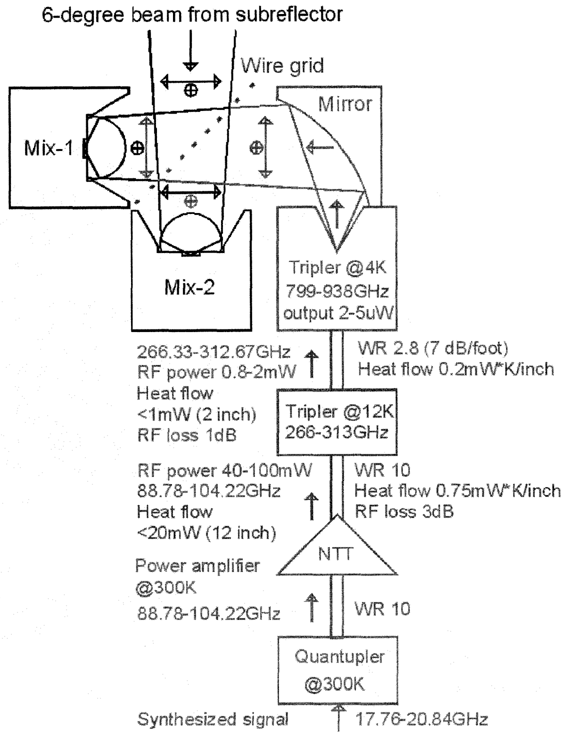

Fig. 2. Optical scheme of double-polarized receiver including quasioptical balanced SIS mixer and tunerless LO chain.

B. Single-chamber waveguide SIS mixer

The new single-chamber waveguide DSB balanced SIS mixer presented in Fig. 3 can be used with a corrugated horn antenna launcher. Two equal probe-type SIS chips are inserted into a full-height waveguide through its broad walls, so the two mixers are driven from the signal waveguide port in series. The LO current is transferred to the mixers in parallel via a capacitive probe inserted through the narrow wall. This LO probe is an extension of a microstrip line which is penetrating into a neighbouring LO waveguide as shown in Fig. 3. The mechanical approach assumes a flat backpiece (backshort) for the signal waveguide, which is designed using the split-block technique (E-plane symmetry). The LO waveguide is to be split along the wide (common) wall, since the small RF loss or/and some non-flatness are not so important for the LO

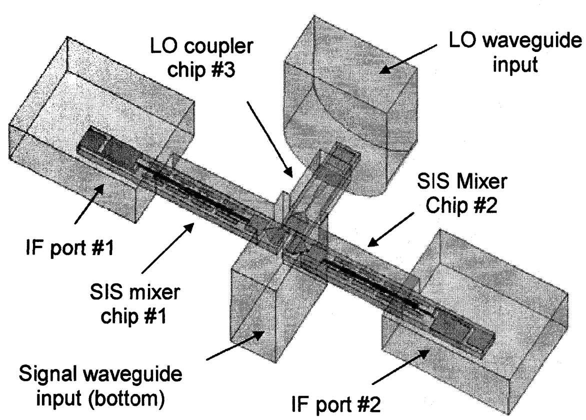

Fig. 3. HFSS 3-D model of THz-range waveguide balanced SIS mixer.

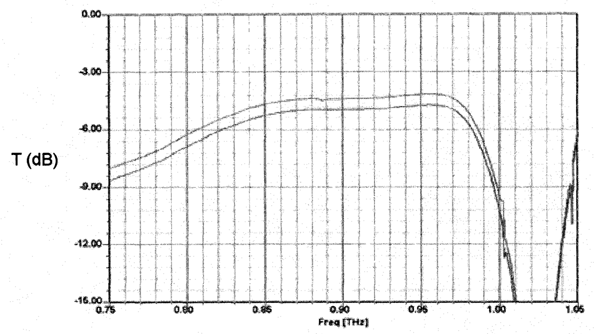

Fig. 4. Transmission of LO power to Mixer 1 and Mixer 2 of the waveguide balanced SIS mixer from Fig. 3 in presence of 10-micron misalignment of the LO-probe chip. Note difference of about 0.5 dB.

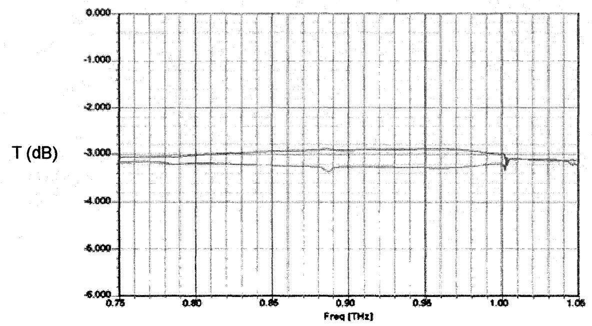

Fig. 5. Transmission of signal to Mixer 1 and Mixer 2 of the waveguide balanced SIS mixer from Fig. 3 in presence of 10-micron misalignment of the LO-probe chip. Note difference of less than 0.5 dB.

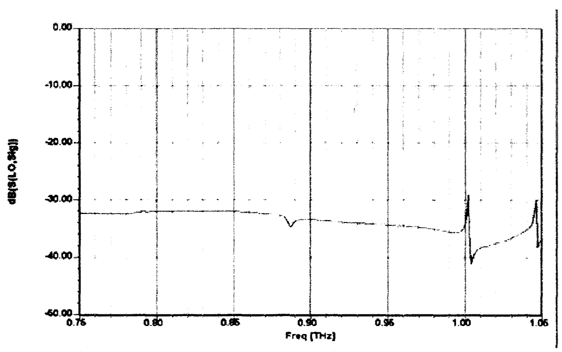

Fig. 6. Signal-to-LO port isolation for the waveguide balanced SIS mixer from Fig. 3 in presence of 10-micron misalignment of the LO-probe chip.

path.

Both signal and LO chips are simulated with HFSS. The simulation demonstrated the LO power coupling efficiency above -3 dB, the signal reflection loss below -20 dB across whole band and the LO cross-talk below -30 dB that take into account the possible 10-um misalignment of the chips. These numerical results are presented in Fig. 4, Fig. 5 and Fig. 6.

III. Twin-Junction Mixer Analysis

We have developed a numerical method based on the Tucker's theory (3-port) and solved the I-V curves of the twin-SIS junction separately. The simulated circuit is tuned

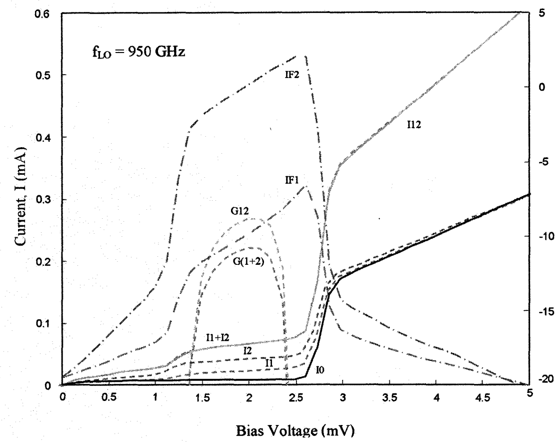

Fig. 7. Simulated I-V curves of the individual junctions of a twin-SIS mixer at 950 GHz. Curves are denoted as following: I0 – un-pumped IV-curve of one SIS junction, I1 and I2 – pumped junction 1 (SIS1) and unction 2 (SIS2), I12 – IV-curve of the equally pumped single junction mixer, IF1 and IF1 – IF current amplitudes generated by SIS1 and SIS2 (i. e. output currents), G12 – mixer gain calculated for equivalent SIS junction I12, G(1+2) – gain calculated with currents IF1 and IF2 for unequally pumped pair SIS1+SIS2.

covering whole ALMA Band-10 with roll-off less than 1 dB at 950 GHz. This case represents a mixer from Fig. 1 (Mixer 1 or Mixer 2). The effect of unequal pump is clearly demonstrated in Fig. 7. The junction with lower pump is shunting the common IF load (LNA) being essentially less efficient at IF. For this reason the mixer gain drops about 3 dB, if compare to the gain predicted with equivalent SIS junction. This seems a general property (problem) of a twin- or multi-junction SIS mixer with the parallel RF connection. Note that twin-SIS mixer with series RF feed [5], [6] has always equal condition for both junctions and thus providing a better performance.

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References

[1] *Virginia Diodes Inc.* [Online]. Available: http://www.virginiadiodes.com .
[2] S. M. X. Claude, C. T. Cunningham, A. R. Kerr, S.-K. Pan, "Design of a Sideband-Separating Balanced SIS Mixer Based on Waveguide Hybrids" ALMA Memo 316, 20 September 2000 [Online]. Available: http://www.alma.nrao.edu/memos/html-memos/alma316/memo316.pdf
[3] T. Noguchi, K. Sunada, J. Inatani, "An SIS mixer with integrated tuning circuit (II) - A proposal of SQUID-type mixer," *Proc. 39th Spring Meeting of the Japanese Society of Appl. Physics,* Tokyo, Japan, p. 76, March 1992.
[4] J. Zmuidzinas, H. G. LeDuc, J. A. Stern, and S. R. Cypher, "Two junction tuning circuits for submillimeter SIS mixers," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 698–706, Apr. 1994.
[5] M. Bin, M. C. Gaidis, J. Zmuidzinas, T. G. Phillips, H. G. LeDuc, "Low-noise 1 THz niobium superconducting tunnel junction mixer with normal metal tuning circuit," *Appl. Phys. Lett.*, vol. 68, pp. 1714–1716, 1996.
[6] S. Shitov, B. Jackson, A. Baryshev, A. Markov, N. Iosad, J. Gao, T. Klapwijk, "A low-noise double-dipole antenna SIS mixer at 1 THz," *Physica C*, vol. 372, no. 1, pp. 374–377, 2002.
[7] Y. Uzawa, Z. Wang, A. Kawakami, "Terahertz NbN/AlN/NbN mixers with Al/SiO/NbN microstrip tuning circuits," *Appl. Phys. Lett.*, vol. 73, no. 5, pp. 680–682, 1998.

[8] G. Chattopadhyay, F. Rice, D. Miller, H. LeDuc, J. Zmuidzinas, "A 530-GHz balanced mixer," *IEEE Microwave Guided Wave Lett.*, vol. 9, no. 11, pp. 467-469, Nov. 1999.

[9] S. Padin, D. P. Woody, J. A. Stern, H. G. LeDuc, R. Blundell, C. E. Tong, M. W. Pospieszalski, "An integrated SIS mixer and HEMT IF amplifier," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 987-987–990, June 1996.

[10] D. Filipovic, S. Gearhart, and G. Rebeiz, "Double-slot antennas on extended hemispherical and elliptic silicon dielectric lenses," *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 1738–1749, Oct. 1993.

[11] M. J. M. van der Vorst. *Integrated lens antennas for submillimetre-wave applications.* PhD thesis, ISBN 90-386-1590-6. Technical Univ. of Eindhoven, Netherlands, Apr. 1999.