Design of 345 GHz Sideband Separation SIS Mixer

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Abstract
We present a design of a 275-370 GHz sideband separation mixer (2SB) where all the superconductor-insulator-superconductor (SIS) junctions, tuning circuitry lines, local oscillator (LO) directional coupler and bias-T are integrated on a single substrate (mixer chip). The RF signal is divided equally with 90º-phase shift by a quadrature waveguide hybrid. The outputs of the hybrid are coupled to the mixer chip through a novel waveguide-to-microstrip transition with integrated bias-T. This structure allows coupling the input waveguide signal to the SIS junction and tuning circuitry lines via a radial type probe while having an isolated port at the opposite side of the substrate where the IF signal can be extracted and DC current injected to bias SIS junctions or suppress Josephson effect independently for each junction. The LO and RF are combined via a 17dB directional coupler, made with superconducting microstrip lines coupled trough lumped links achieved by two perforation slot-holes in the ground plane.

Keywords: Sideband separation, SIS mixer, waveguide probe, bias-T.

1. INTRODUCTION

This mixer is designed for APEX 12m telescope, which is currently under construction in the Chajnantor region of Northern Chile at an altitude of 5000m, in the Atacama Desert. This site, probably the driest on Earth, is one of the best for sub-millimetre wave observations, together with the South Pole and Mauna Kea in Hawaii [1]. The antenna is a prototype of the ALMA antennas, but with improved surface accuracy (18 µm rms) to allow higher frequency operation and with a modified sub-reflector to accommodate multi-channel arrays. This telescope will have both heterodyne and continuum instruments, covering the frequency range (230 GHz–1.5 THz). The work presented here is done for APEX band 3, covering the frequency range 275-370 GHz (which coincides with ALMA band 7), with centre frequency at approximately 345 GHz. This receiver was chosen to be of sideband separation type, a technology pioneered in millimetre waves by NRAO [2]. Indeed, the noise performance of double sideband (DSB) super heterodyne receiver can be limited by the atmospheric noise fed into the system via the image band. At 345 GHz, receiver sensitivity is improved with a 2SB mixer compared to a DSB mixer [3].
In the proposed design, sideband separation is achieved using a quadrature scheme as in Fig. 1. The RF signal is divided equally with 90° phase difference, and the local oscillator (LO) is also divided equally and applied to 2 identical DSB mixers.

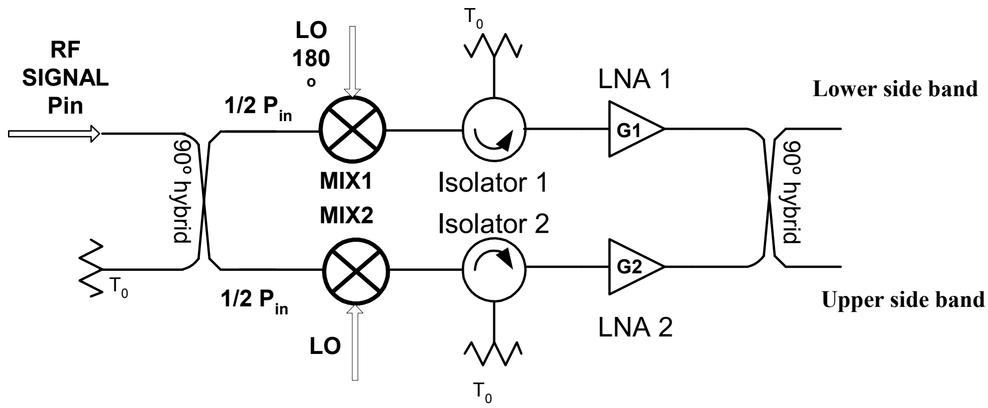


Fig. 1: Block diagram of the sideband separation mixer.

The mixers outputs at intermediate frequency (IF) are connected to cryogenic IF low noise amplifiers (LNA) having isolators at their input to avoid oscillations. The outputs of the LNAs are then connected to a quadrature 3 dB hybrid. Since one of the sidebands is combined in phase and the other out of phase, sideband cancellation occurs and both sidebands appear separated. The degree of sideband suppression is dependent on the symmetry in amplitude and phase of both paths. Placing the LNAs before the IF hybrid improves the system noise performance as there are no additional losses from the IF hybrid.

2. SIDEBAND SEPARATION MIXER LAYOUT

Our design is based on the previous development of a 2SB mixer for 85-115 GHz [4], whose initial results confirms the capability of such integrated structure. Fig. 2 shows a proposed layout for the 2SB mixer for 345 GHz. The quartz substrate will have dimensions of about 5 mm x 200 µm x 65 µm. The mixer block will be built using the split-block technique and consists of two parts dividing symmetrically all waveguide structures. The bottom part of the mixer block will accommodate the mixer substrate and the termination of the idle port of RF hybrid. The RF signal coming from a corrugated horn, enters through the waveguide hybrid, and is divided equally in magnitude with 90° phase difference. The waveguide hybrid outputs are then coupled to the mixer substrate through a radial probe built on the quartz substrate. The probe impedance is about 40 Ω. The LO signal enters through the opposite end of the mixer block, and is coupled to the substrate and divided equally in magnitude with 180° phase difference through a double probe transition (Fig. 3). The LO signal is then coupled to the RF path through a 17 dB directional coupler, made with superconducting lines coupled via lumped links, two perforation slot-holes in the ground plane (shaped as a choke). The two IF outputs are then extracted from the sides of the mixer block.

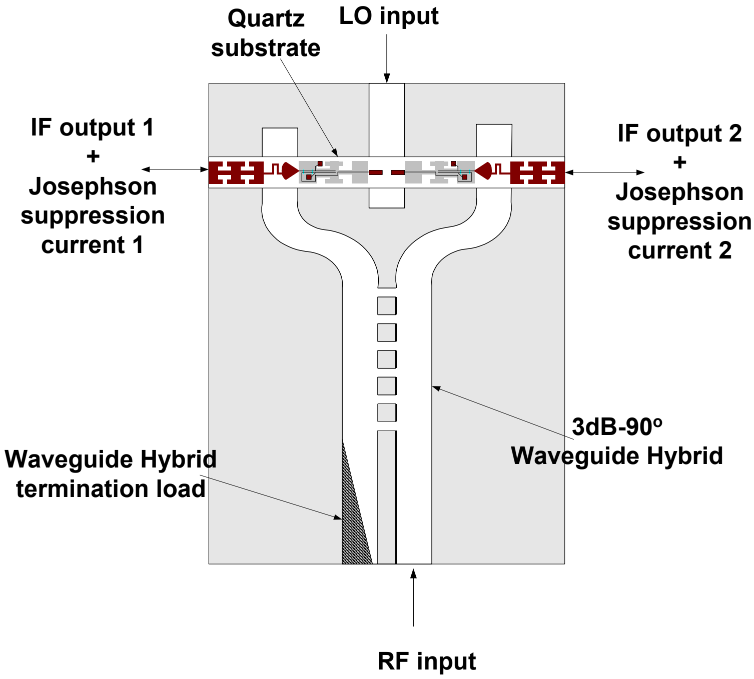


Fig. 2: 2SB mixer for 345 GHz

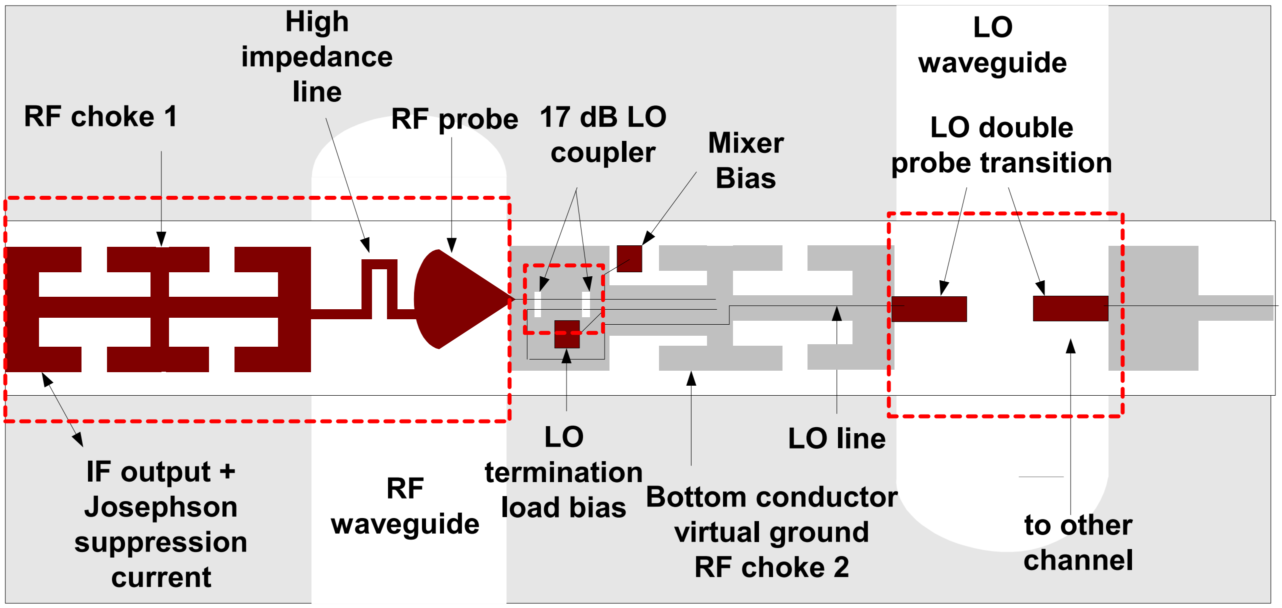


Fig. 3: Enlarged view of the left part of the 345 GHz mixer. Dashed areas indicate components that will be describe in more details in the next part.

One of the main differences with the 100 GHz 2SB mixer [4] is that for high frequency receiver, Josephson effect [5] has to be suppressed, and to do so, a magnetic field has to be applied parallel to the SIS junction. The standard solution is to use superconducting coils to apply external magnetic fields. However for our design of sideband separation mixer on a single substrate, the spacing between the 2 SIS mixer junctions becomes very small, therefore it becomes quite difficult to use separate coils without having unwanted crosstalk, or it is physically too tight. An alternative is to inject DC current through built-in lines creating local magnetic fields around the superconducting control lines, which will be parallel to the SIS junctions and will therefore suppress Josephson currents [6]. In the proposed design the RF probe is connected on its wide side to another port via a specially shaped high impedance line that provides RF/DC isolation. This port will be used to extract the IF signal and to inject DC current to suppress Josephson currents. Choke structures are used to filter out the RF signals. For the IF/DC paths, a choke structure (choke 1 in Fig. 3) provides a virtual ground in the waveguide wall. Another choke structure (choke 2 in Fig. 3) is deposited on top of the quartz substrate in order to provide effective ground for the top superconducting lines. In the next part, we describe in more detail the different components of the mixer.

3. MIXER COMPONENTS

3.1. Waveguide to microstrip transition with integrated bias-T

We designed a waveguide-to-microstrip transition with an integrated wide band bias-T [7]. The novelty of this probe comes from the fact that it couples the input waveguide signal to the SIS junction and tuning circuitry lines via a radial probe (see Fig. 4) while having an isolated port at the opposite side of the substrate where the IF signal can be extracted and DC current injected to bias SIS junctions or suppress Josephson effect independently for each junction. In the suggested probe structure, the input waveguide couples the RF signal to the output microstrip line and is isolated from the DC-IF microstrip line. The substrate is crystal quartz placed in channels with sub-critical dimensions to prevent propagation of unwanted waveguide modes. The RF probe is a radial line with a radius occupying 40 % of the waveguide height and has an impedance of approximately 40 Ω. We use an RF choke in the DC/IF channel, to get a virtual ground in the waveguide wall plane, then we connect it to the radial probe with a (2n-1)λ/4 long and very high impedance line. An X-band version of the probe has been constructed (Fig. 5.a) and tested. Measurements are compared with simulated results in Fig. 5.b.

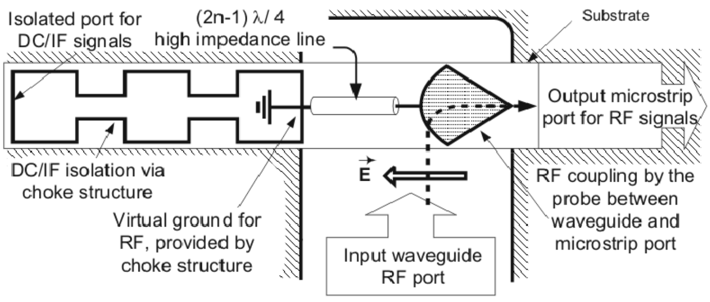
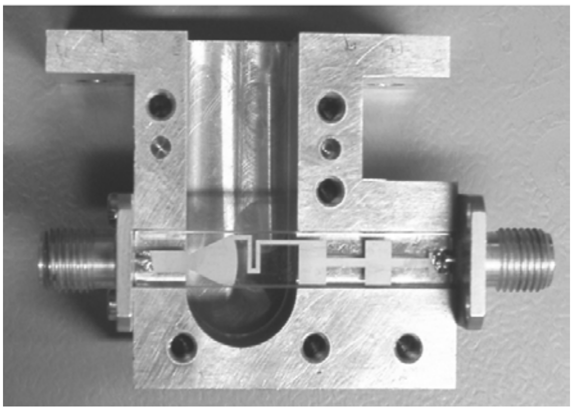
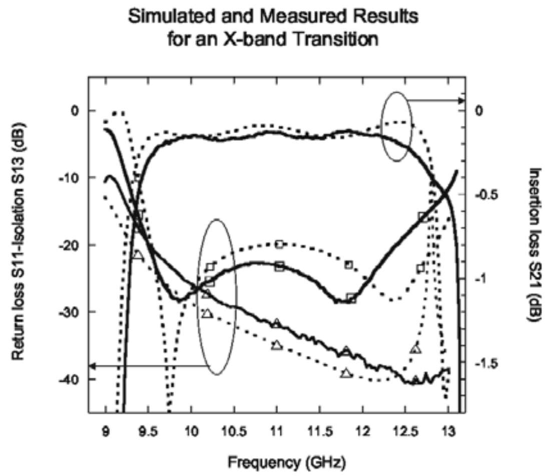


Fig. 4: The probe structure



a) Photograph of the split part of the X-band transition. Split-block techniques is used, cylindrical backshort is done to facilitate fabrication at high frequencies.



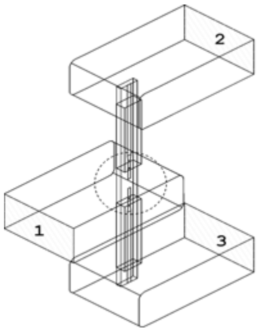
b) Measured and simulated results: upper curves are insertion loss, middle curves with squares are return loss and lower curves with triangles are isolation between RF and DC-IF ports.

Fig. 5: X band scale model of the probe transition.

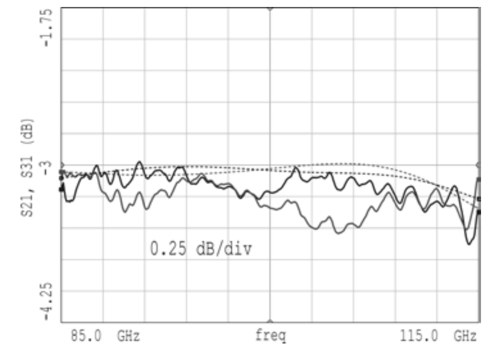
The simulated results include microstrip losses as well as SMA connector losses. Measured insertion loss is about –0.15 dB across the band (9.5-12.5 GHz), and includes losses from the SMA connector, conductor losses and quartz losses. Return loss is better than –20 dB, and isolation between RF ports and the DC-IF port is better than -20 dB. Agreement with the HFSS simulation is excellent with the RF bandwidth achieved of 30 %.

3.2 LO waveguide to microstrip double-probe transition

To achieve a simple design combining low-loss, wide-band symmetrical power division and the waveguide-to-microstrip transition for the LO signal, we employ a double-probe structure [8] coupled to the E-field in the input waveguide 1, as shown in Fig. 6.a. The transition has a simple geometry and does not require any lumped termination load, which is difficult to fabricate with satisfactory accuracy using thin film technology. Scalar measurements of the waveguide to microstrip double probe transition were performed at 85-115 GHz. To facilitate the measurement, additional microstrip to waveguide transitions were designed forming a waveguide-to-waveguide 3-dB power divider as shown in Fig. 6.a. The transmission S21 and S31 is plotted in Fig. 6.b, the typical total loss is ≈0.3dB over 30% of the bandwidth and it includes the losses from the single waveguide to microstrip transitions.



a) Waveguide to microstrip power divider as it was measured at 100GHz. The microstrip ports were replaced with microstrip to waveguide transitions. The waveguide is WG-10, the structure dimensions are S=340 μm, W=95 μm, L=270 μm and the substrate cross section is 610x150 μm

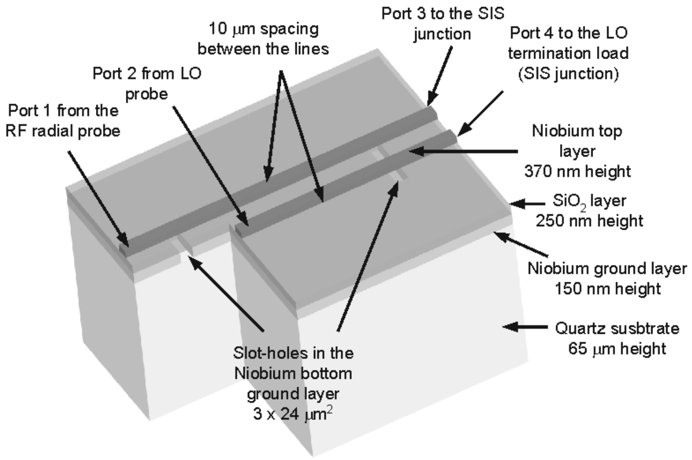


b) Measured transmission S21 and S31 of the double probe transition (solid lines) and the simulated transmission (dashed lines).

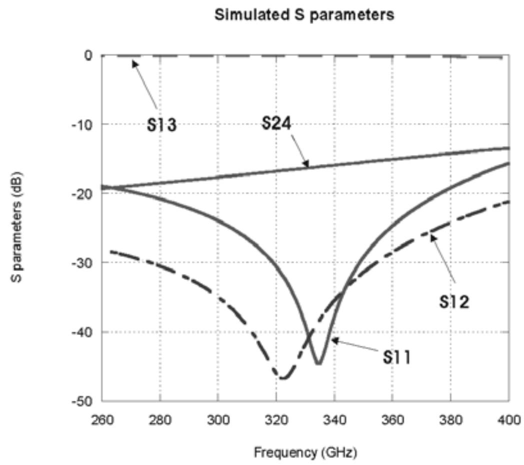
Fig. 6: The double probe: structure and results.

3.3. LO directional coupler

The LO directional coupler made with superconducting lines is shown in Fig. 7. The LO signal input (port 2) comes from the waveguide-to-microstrip double probe transition and the RF signal (port 1) comes from the radial probe.



a): Cross section drawing of the LO directional coupler. Dimensions are exaggerated to clarify the picture. Spacing between the slots is 60 μm.



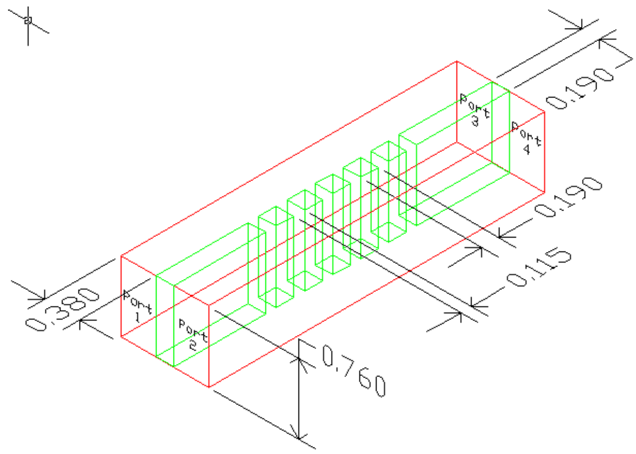
b) Simulated results: Coupling is between 15 and 19 dB across the band and return loss and isolation are better than 20 dB.

Fig. 7: LO directional coupler: structure and simulated results.

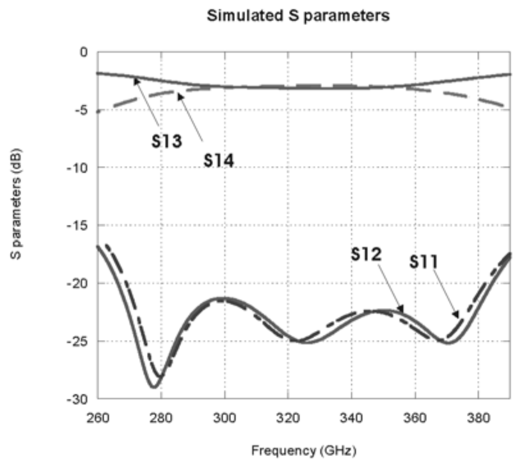
The LO directional coupler uses the same dielectric as the SIS junction and RF tuning circuitry (250 nm of SiO_2). In order to provide 17 dB coupling, if standard coupled lines were used, the required spacing between the lines would be less than 1 µm and therefore would be difficult to be produced with the required accuracy with optical lithography. In the proposed coupler, the spacing between the lines is 10 µm and the 17 dB coupling is provided by two perforation slot-holes of dimensions 3 x 24 μm^2, in the ground plane of the superconducting line (middle choke structure in Fig. 3). The idle port of the LO coupler (port 4) must be terminated with matched impedance, an SIS junction identical to the one used for mixing (port 3) was found to be suitable to provide required termination [9]. The simulated results shown in Fig. 7.b predict a coupling between 15 and 19 dB, with return losses and isolation better than 20 dB.

3.4. Waveguide 3 dB 90° hybrid

This component is needed to divide equally the RF signal with a 90° phase difference. To reach a bandwidth of 30%, several sections are required, about 6 or 7 sections are necessary. The problem with increasing the number of sections is that the required dimensions become very small, and thus are difficult to be produced. Fig. 8.a shows an HFSS model drawing of such a structure with 6 sections and Fig. 8.b shows the simulated S parameters of this device. The magnitude imbalance is of ±0.5 dB around –3 dB at worse in the band of interest (between 275-370 GHz).



a): HFSS drawing of the waveguide 3 dB-90° hybrid, dimensions are in millimetres.



b): Simulated results, coupled signals are about –3 dB, and return loss and isolation are better than –20 dB..

Fig. 8: Waveguide 3 dB-90° Hybrid

3.5. SIS junction and tuning circuitry

The SIS junctions are fabricated by GARD at Chalmers new clean room facility. The designed Nb-AlOx-Nb SIS junctions are expected to have an area of 1.5 x 1.5 μm^2, a critical current density (Jc) of 10 kA/cm^2 resulting in a normal resistance (Rn) of 10 Ω. The equivalent circuit of the SIS junction at RF is shown in Fig. 9.

To match the complex impedance of the SIS junction to the nearly real impedance of the signal source (probe), Cj should be resonated out at RF. We used a short microstrip line, equivalent to inductance, L_t, at RF, connected in parallel. A λ/4 open stub provides ground for L_t. R_{RF} is then matched to the RF source impedance by a λ/4 transformer. SIS impedance in presence of LO power is derived with the help of a program, which calculates R_{RF} vs. frequency and LO pumping power based on the measured or modelled IV characteristic of the junction [5].

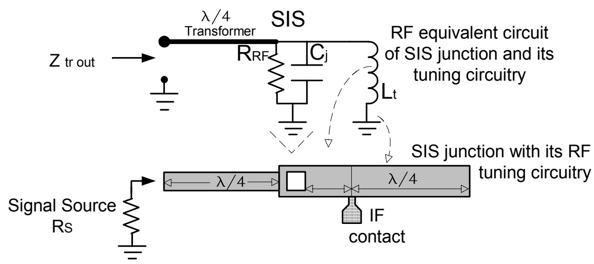


Fig. 9: Equivalent circuit of SIS junction and its tuning microstrip-based circuitry at RF. The impedance of the pumped SIS junction, R_{RF}, connected in parallel with its geometrical capacitance C_j. A piece of line acting as inductance, L_t, grounded via λ/4 open stub, resonates C_j at RF centre frequency. The impedance R_{RF} is matched to the RF source impedance R_S via a λ/4 transformer.

The impedance of the signal source is considered as the output impedance of the radial probe derived using HFSS.

4. CRYOGENIC ISOLATORS AND IF LOW NOISE AMPLIFIERS

The IF bandwidth for the mixer is chosen to be from 4 to 8 GHz. The cryogenic IF LNAs were developed at Onsala [10]. They are two stage amplifiers having GaAs HEMTs Mitsubishi MGFC4419G. Noise temperature at 4K is of about 5K with 26 dB gain across the band. They have very consistent performance and are very similar, e.g., gain (± 0.5 dB) and phase (± 5°), which is very important not to degrade the sideband separation ratio of the bands. The amplifiers are used with cryogenic isolators produced by Domen Co. [11] and having about 0.2-0.3 dB insertion loss at 4 K across the band of 4-8 GHz.

5. CONCLUSION

We present the design of a sideband separation for 275-370 GHz. The mixer is based on a new device, a double probe coupler, which makes possible the integration of all mixer components on the same compact substrate and thus ensures a high degree of similarity in the SIS junction performance and the geometry of all mixer elements. Furthermore a novel waveguide probe with integrated bias-T was introduced, allowing to extract IF signals and to inject DC current to suppress Josephson effect in the high frequency SIS mixers conveniently. Construction of the mixer has started and installation of the receiver at the APEX telescope is planned beginning of 2004.

6. ACKNOWLEDGMENT

The authors would like to thank Professor Roy Booth for always providing us with remarkable support and encouragement for successful completion of this work. M. Fredrixon, our computer wizard, is greatly appreciated for his support of our computation and measurement activities. This work is funded under Contract #KAW20010312 for APEX project by the Wallenberg Foundation.

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