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Simple 1 mm receivers with fixed tuned double sideband SIS mixer and wideband InP MMIC amplifier

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ABSTRACT

We report on attempts to broaden the IF bandwidth of the BIMA 1mm Superconductor-Insulator-Superconductor (SIS) heterodyne receivers by combining fixed tuned Double Side Band (DSB) SIS mixers and wideband MMIC IF amplifiers. To obtain the flattest receiver gain across the IF band we tested three schemes for keeping the mixer and amplifier as electrically close as possible. In Receiver I, we connected separate mixer and MMIC modules by a 1″ stainless steel SMA elbow. In Receiver II, we integrated mixer and MMIC into a modified BIMA mixer module. In Receiver III, we devised a thermally split block where mixer and MMIC can be maintained at different temperatures in the same module – in this receiver the mixer at 4 K sees very little of the 10–20 mW heat load of the biased MMIC at 10 K. The best average receiver noise we achieved by combining SIS mixer and MMIC amplifier is 45 -50 K DSB for ν_{LO} = 215–240 GHz and below 80 K DSB for ν_{LO} = 205 - 270 GHz. Over a 1 – 4 GHz IF we have demonstrated receiver DSB noise temperatures of 40 – 60 K. Of the three receiver schemes, we feel Receiver III shows the most promise for further development.

1. Introduction

The Berkeley-Illinois-Maryland Array (BIMA) and the Caltech Owens Valley Radio Observatory Array (OVRO) telescopes will merge to form the Combined Array for Research in Millimeter-Wave Astronomy (CARMA) in 2005. Each element of the new telescope array[1] will be equipped with a cooled 1 mm receiver consisting of a Superconductor-Insulator-Superconductor (SIS) mixer with Intermediate Frequency (IF) postamplifier. Downconverted signals from each element will be processed by a correlator with a total bandwidth of 4 GHz. Whereas the current OVRO 1 mm receivers[2] cover an IF band of 1 - 5 GHz, the present BIMA receivers use IF postamplifiers which cover only 1.4 – 2.2 GHz (L band). Before integrating BIMA instrumentation with CARMA, receiver IF bandwidths must be expanded to at least the CARMA correlator bandwidth. The resulting wide instrumental bandwidth will greatly facilitate the study of molecular transitions and continuum radiation. This paper describes our progress towards building wideband receivers by combining existing 1 mm SIS mixer chips developed for BIMA with 0.5 – 11 GHz MMIC amplifiers developed for the Allen Telescope Array frontend[3,4].

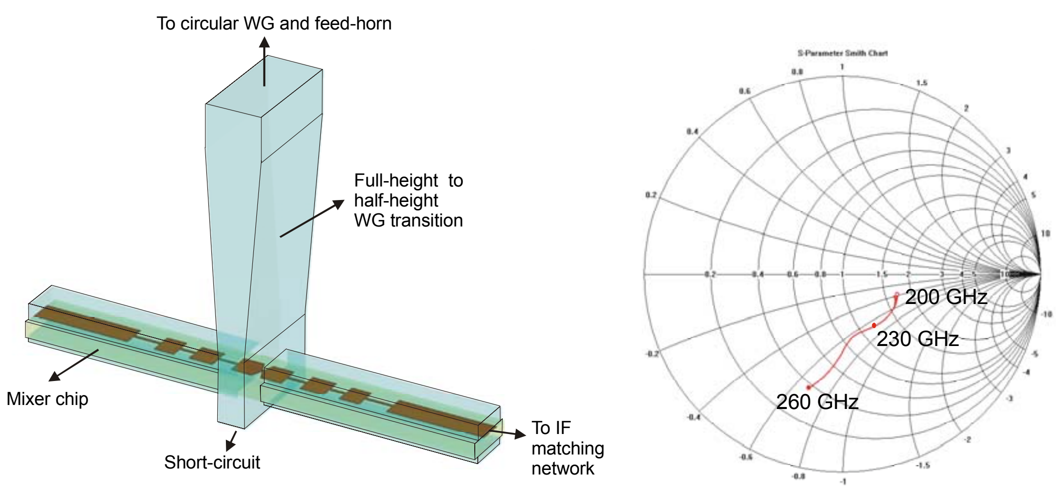


Figure 1: (left) Inner structure of the mixer showing the butterfly probe embedded in half height waveguide and the transition to full height waveguide. (right) Antenna driving point impedance in the 200-260 GHz frequency band.

2. Narrow IF band 1 mm receiver at BIMA

The BIMA 1 mm SIS mixer design was adapted by G. Engargiola and R.L. Plambeck[5] from a mixer design developed by Blundell *et al*.[6] for the Submillimeter Array.

2.1 Waveguide Mounting Structure

The 1 mm mixer block has a circular waveguide input of 0.050" diameter which transitions over a distance of 0.125" into WR4 full height waveguide, which then transitions over a similar distance into a WR4 half height waveguide. Figure 1 (left) shows a view of the internal waveguide structure where the mixer chip is embedded. The guided RF input couples to the SIS mixer through a wideband butterfly probe on a 0.005" thick z-cut quartz substrate extending across the half-height waveguide.

The substrate is suspended in a channel with a 0.006" air gap above and a 0.0025" air gap below, with the metallization facing the RF input direction (from above). The feed structure is centered over a fixed tuned ~$\lambda_g/4$ deep waveguide cavity that guarantees a broadband DSB coupling into the junction. A low-pass filter rejects RF energy propagating in the substrate channel. Figure 1 (right) shows the antenna driving point impedance derived from the results of a full wave simulation performed with finite difference time domain method software. Across the 200 - 260 GHz RF band the real part of the antenna impedance varies over ~20 - 80Ω, while the imaginary part remains ~-j 30 Ω (approximately a constant capacitance).

2.2 RF Matching Structure

To achieve the RF tuning bandwidth of ~60 GHz, we chose a $R_n \times A$ product of ~29 $\Omega \times \mu m^2$. With a junction specific capacitance of ~70 $fF/\mu m^2$ this corresponds to a quality parameter factor of $Q_{RF} = \omega R_{RF} C \sim 2.0$ at mid band, based on a small-signal RF impedance $R_{RF} \sim 0.69\ R_n = 13.8\ \Omega$ at 230 GHz. A junction area of 1.2 x 1.2 μm^2 was chosen as a compromise between the technological difficulties of fabricating small area junctions with good accuracy and the problem of matching the junction RF impedance to the higher driving point impedance of the waveguide probe. The Nb/Al-AlO_x/Nb SIS junction capacitance of $C_j \sim 100$ fF is RF tuned by a series inductor realized as a $\sim\lambda/8$ long superconducting microstrip line (an end-loaded stub) with a 200 nm thick SiO dielectric ($\varepsilon_r \sim 5.6$). The impedance of the tuned junction has a small real value $\sim R_{RF}/2Q^2 \sim 1.7\ \Omega$. A two-section quarter wave transformer matches the tuned junction impedance to the antenna impedance. The matching section is implemented in superconducting microstrips patterned on top of the RF choke filter above a 400 nm thick SiO layer. The thickness of the trilayer, etched to produce the SIS junction, is 250 nm. The trilayer also defines half the RF filter and butterfly antenna structure. The thickness of the Nb wiring layer, which defines the RF matching structure, the tuning stub, and the other half of the RF filter and antenna, is 450 nm. A view of the BIMA mixer chip in an open mixer block is shown in Figure 2.

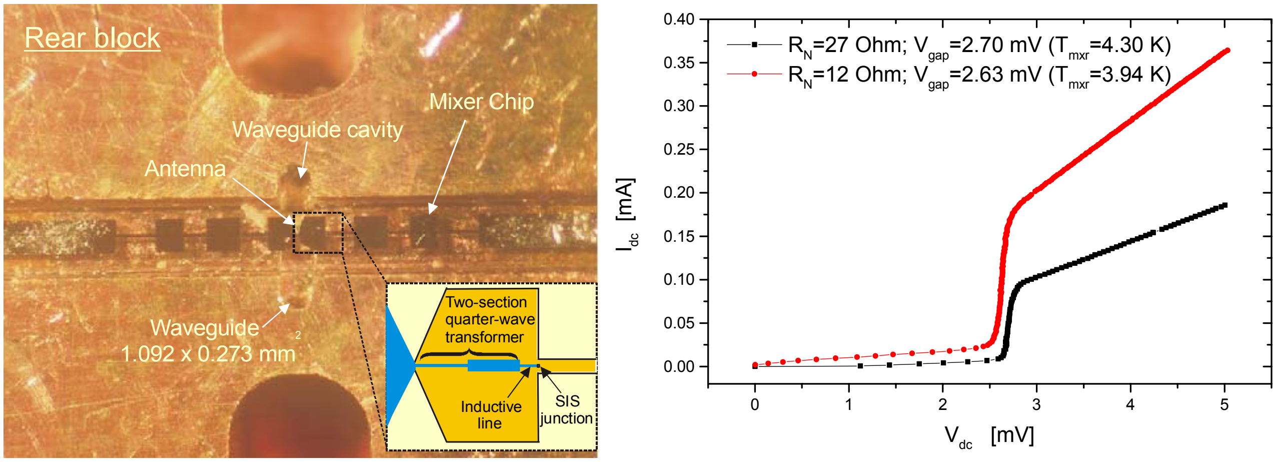


Figure 2 (left) Close-up view of the BIMA SIS mixer chip and (right) typical I-V characteristics for these devices.

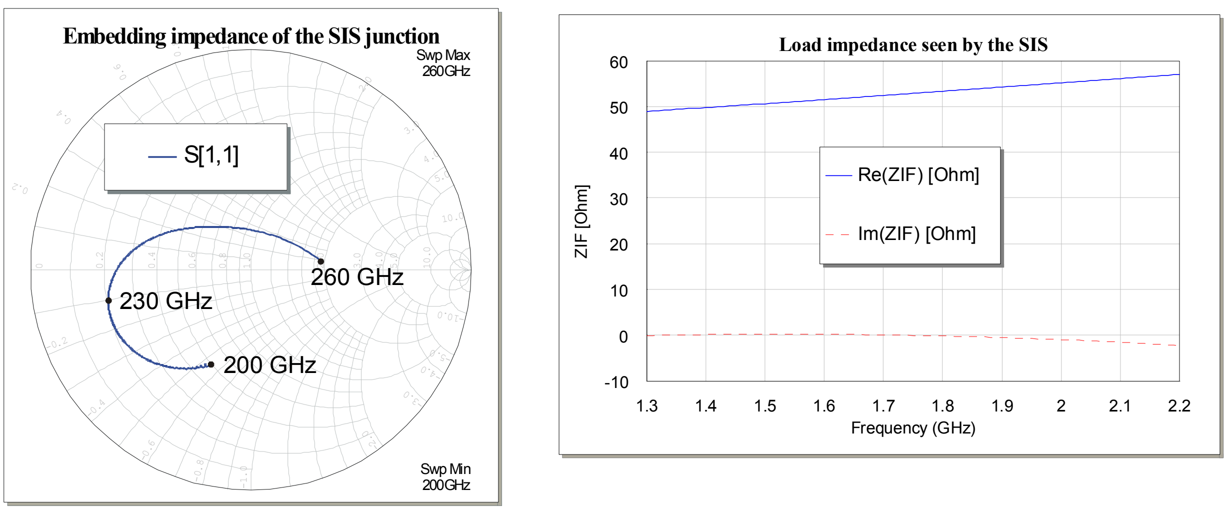


Figure 3 (left) RF impedance seen by the junction. The Smith Chart is normalized to the frequency dependent small signal RF impedance of the junction R_{RF}, where R_{RF}=18.6 Ω at 230 GHz and R_n=27 Ω. (right) Impedance seen at IF frequency by the SIS junction.

Representative I-V characteristics, shown next to the photo, indicate a range of device characteristics resulting from junction and circuit dimension design variations. For a typical junction, the normal resistance is 12 - 27 Ω, and the ratio of the subgap to normal resistance is $R_{sg}/R_n \sim 10$. Figure 3 on the left indicates the result of an electromagnetic simulation for the RF impedance seen by the SIS junction for 200-260 GHz. This is the impedance of the antenna/waveguide structure seen through the superconducting RF matching network. In our model, field penetration in the superconducting lines is taken into account.

2.3 IF Matching Structure

Empirically, we found that receiver noise temperature depends only weakly on the impedance match between the mixer and 50 Ω coaxial line linking the L band LNA so we used a short section of 50 Ω microstrip on Duroid 5880 to couple the mixer IF pad to its SMA output connector. Electromagnetic simulations of the mixer structure at IF show that this simple circuit results in an almost ideal network by presenting an impedance at the IF port of the SIS with real value of 2-3 R_n~50 Ω over the 1.4-2.2 GHz band (see Figure 3, right). An approximation of the IF quality parameter $Q_{IF} \cong \omega Z_{IF}(C_j+C_{match})$ ~1.3 at 3 GHz can be made from estimates of the pumped impedance of the junction (~$10*R_n \cong 200\ \Omega$) in parallel with the parasitic junction capacitance (C_j~100 fF) and the low frequency capacitance of the RF matching network (~ 250 fF). The low value suggests that a wide relative IF band can be covered using this mixer within the specifications of the CARMA project. Widening the IF band of our SIS 1 mm receiver without degrading its instantaneous band noise performance can be attempted most simply by connecting the mixer to a MMIC amplifier with wide bandwidth, high gain, and low noise through a suitable IF network.

2.4 Mixer Fabrication

G. Engargiola fabricated the SIS chips at the Material Research Laboratory at the University of Illinois, Urbana-Champaign. He developed a five-layer fabrication process, where each layer was patterned by photolithography and liftoff. First a large area Nb/Al-Al_2O_3/Nb trilayer is deposited on

0.005" thick crystalline quartz to form half of the symmetric RF feed-structure and low-pass filter. The junction is defined in two steps. A 1.2 μm line across the short dimension of a long, narrow rectangular window is patterned in photoresist on the trilayer, and the 100 nm thick Nb counterelectrode on either side of the line is removed by reactive ion etching in a CF_4+O_2 atmosphere. Then a 200 nm thick layer of SiO is thermally evaporated onto the photoresist stencil. The 140 nm thick base Nb electrode of the etched area serves as the ground plane and the SiO layer as the dielectric for the microstrip tuning circuit. After liftoff of the first insulation layer, this process is repeated with a photoresist line orthogonal to the first, which results in a 1.2 x 1.2 μm^2 junction. We used this two-step etching technique because it gives reproducible junction areas and high quality I-V characteristics. While this technique was devised to guarantee high single junction device yields, we found that it actually produces nearly identical yields for large series junction arrays (N > 6).

An additional layer of SiO is deposited on the etched region of the trilayer so that, extending from the RF feed point to the junction, the insulation profile steps from 400 nm down to 200 nm where the two-stage impedance transformer links to the inductively tuned junction. A Nb wiring layer defines the junction tuning circuit and the second half of the RF feed and low pass-filter structure. The two halves of the low-pass filter, electrically connected through the SIS junction and series inductance, provide the current path for the DC bias circuit. In our process, extremely high device yields were obtained with critical current densities of up to 6 kA/cm^2. From the empirical results of Van der Zant et al[7] we infer a specific capacitance for our junctions of 60 $fF\mu m^{-2}$.

2.5 Mixer Results

Despite a range of SIS device characteristics, all 1 mm receivers at BIMA have remarkably similar noise temperatures. Very often, differences in RF bandwidths could be traced to slight misalignment of the waveguide probe relative to the backshort.

Figure 4 shows receiver temperature versus LO frequency for a typical BIMA mixer cascaded with a 1.4-2.2 GHz LNA. Best sensitivities occur between 215 and 240 GHz where $T_{rec,DSB,\ DSB} < 55$ K. Mixer operating temperatures are usually 3.6 – 4.5 K; over this range, $T_{rec,DSB}$ varies less than 5 K Reasonable mixer performance occurs for $\nu_{LO} \sim 205 - 270$ GHz, where $T_{rec,DSB} < 80$ K.

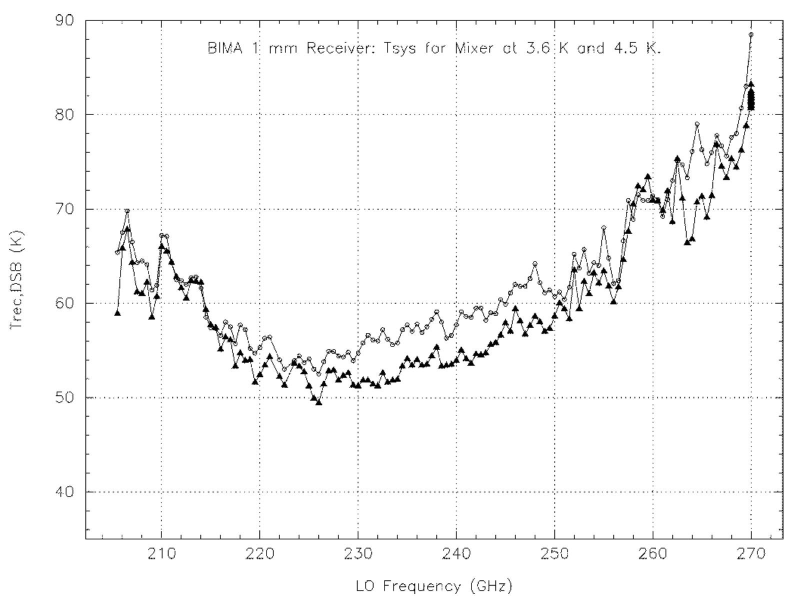


Figure 4 Receiver temperature versus LO frequency for BIMA 1 mm receiver with L band IF amplifier. Filled triangles denote mixer operating at 3.6 K; open circles denote mixer operating at 4.5 K.

3. WIDEBAND MMIC AMPLIFIERS

Kerr *et al.*[8,9] and Lauria *et al.*[10] have produced 1 mm receivers with 4 - 12 GHz IF by following SIS mixers with amplifiers built from discrete transistors. For simplicity we prefer to use MMIC IF amplifiers instead. Wadefalk and Weinreb developed two MMIC devices (WBA12 and WBA13) for the Allen Telescope Array frontend[4] which should be well-suited for CARMA IF postamplifiers. The WBA12 and WBA13 amplifiers include either two or three 0.1 μm InP HEMT stages tuned to be unconditionally stable when attached to any passive load. The chip size is 2 x 0.7 x 0.075 mm^3. At a 10 K operating temperature the WBA12 and WBA13 amplifiers have a noise temperature of T_n ~4 K and gain of ~25 dB and ~35 dB respectively, across a 3 – 11 GHz band. For these devices at 1 GHz, T_n ~ 6 K and gain is 5 dB lower. Figure 5 shows a WBA13 chip, with RF input attached to a

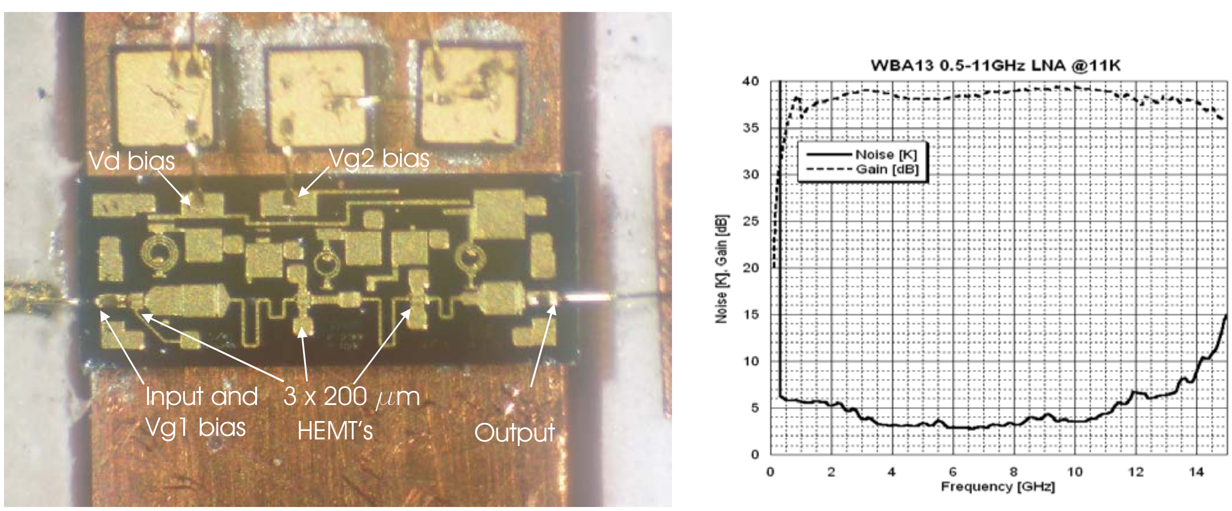


Figure 5 (left) Close-up view of the WBA 13 wideband MMIC amplifier chip. The WBA12 and WBA13 chips are similar circuits with either two or three InP HEMT stages producing ~25 dB and ~35 dB of gain, respectively. (right) Noise temperature and gain of WBA13 amplifier. WBA12 chip has a similar noise versus frequency characteristic but ~10 dB lower gain.

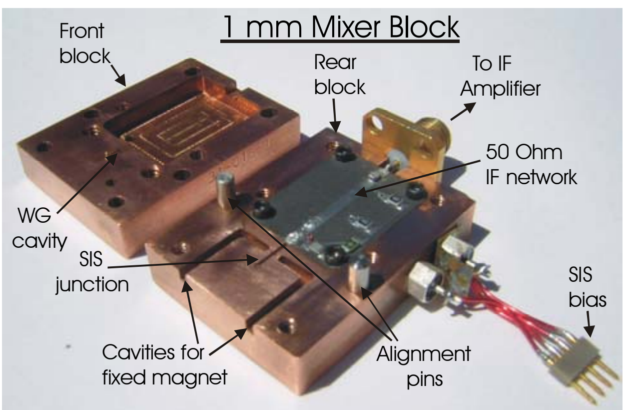
50 Ω matching network and the output attached to a 50 Ω microstrip. The gates are biased through 10:1 voltage dividers and the drain wire provides 10 – 20 mW of DC power.

4. Wide IF band 1 mm Receivers for CARMA

All receivers were tested in a BIMA cryostat, where the LO is injected with a 0.0003" Mylar beam splitter into the dewar input lens. The LO+RF signal is matched to the input waveguide of the mixer with a scalar feedhorn which is bolted to the 4 K stage. Y-factor tests were highly automated. Tuning of the LO, biasing of the mixer, and operation of the chopper wheel were all under computer control. LO power was monitored by measuring the current through the voltage biased mixer. For a cold load we used a thin-walled Styrofoam box containing RF absorbing foam immersed in liquid nitrogen. We did not attempt to correct our noise temperature calculations for optics losses, and we assumed hot and cold load temperatures were 295 K and 77 K, respectively. The receiver IF power was amplified outside the cryostat by a 1 – 10 GHz amplifier module JCA 110-317 with 30 dB gain. Broadband IF power was measured through a DC – 6 GHz lowpass filter with an HP 8484 power sensor attached to an HP 436 power meter. Power levels were computer monitored. Measurements for hot or cold loads were made by setting the LO frequency and power, stepping the mixer bias voltage, and recording the IF power. Best noise temperatures are usually obtained by voltage biasing the SIS junction near the center of the first photon step in the I-V curve. Over the RF band of this device the optimal bias voltage varies from 1.9 – 2.5 mV. Y factor measurements for each frequency were made at optimum LO power level.

(i) Receiver I: SIS mixer followed by WBA13 MMIC coaxial amplifier module

We tried the simplest approach first to increase mixer IF bandwidth, by attaching a BIMA mixer module with SMA connector output to a coaxial module containing a WBA13 MMIC through a 1” section of 0.085” stainless steel semirigid coaxial cable. The cable thermally isolates the 4 K mixer and 10 K MMIC. The devices were attached by heat straps to separate stages of the BIMA cryostat, which is cooled by a three stage Gifford-McMahon refrigerator[11,12]. This arrangement minimizes the heat load from the biased MMIC on the SIS mixer.



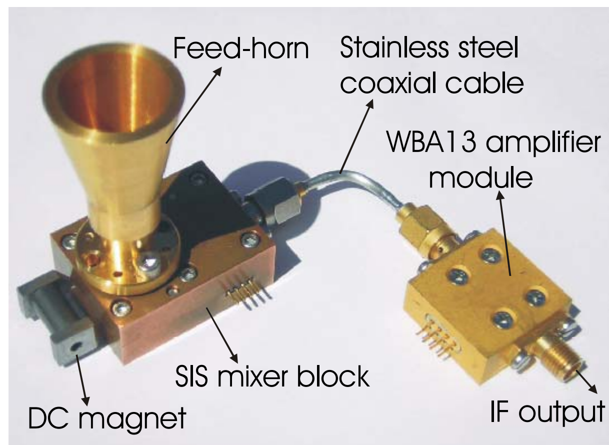


Figure 6 Open view of the BIMA SIS mixer module (left) and view of Receiver I consisting of BIMA mixer module attached to WBA13 amplifier module through 1″ section of stainless steel coax.

Figure 6 shows Receiver I, including an open view of the mixer module (left) and the assembled module attached to the MMIC amplifier module (right). The mixer chip sits in a suspended waveguide channel between the poles of a fixed magnet. The mixer chip IF pad is bonded with a gold wire (1 mil diameter) to a 50 Ω microstrip. A bias tee is shown with series 10 K current limiting resistors on the bias lines and a 100 Ω resistor shunting the junction impedance for stable voltage biasing.

Results of measuring the noise temperature $T_{rec,DSB}$ of Receiver I as a function of LO frequency are shown in Figure 7. The values are often lower than those measured for a BIMA mixer followed by an L band amplifier (Figure 4). From 205 – 240 GHz $T_{rec,DSB}$ is 7 - 10 K lower. At the high frequency end of the band, $T_{rec,DSB}$ is about the same. Discrepancies between Receiver I and the BIMA receiver noise temperatures may be due to loss in a longer (10") IF coaxial cable connecting the SIS mixer to the L Band LNA in the BIMA receiver.

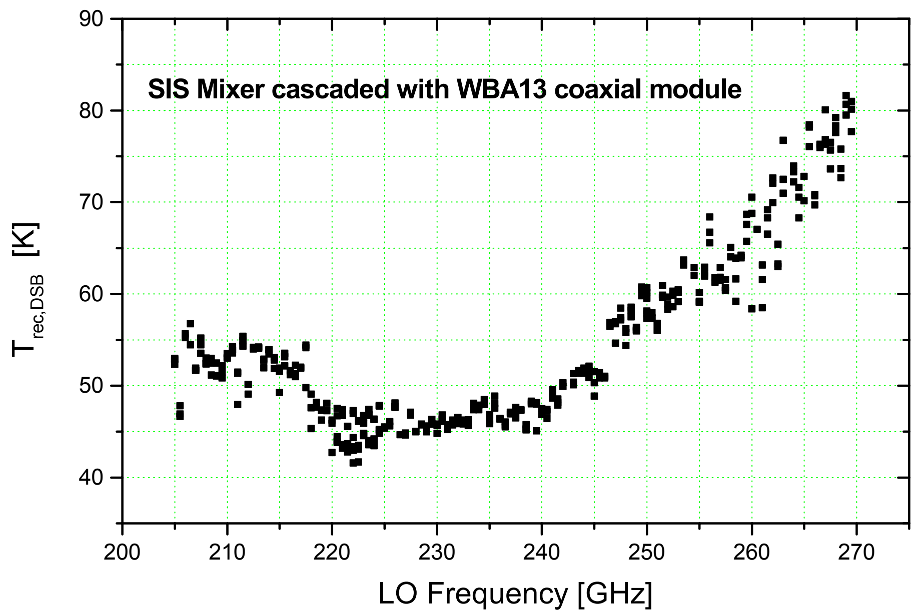
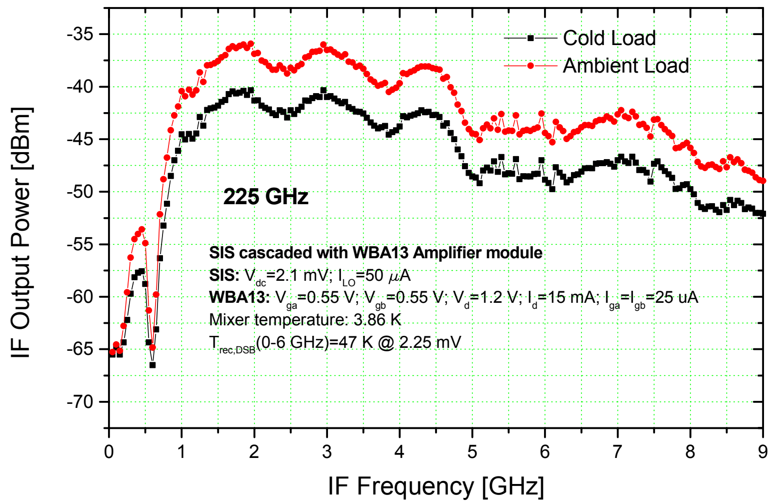


Figure 7 Receiver temperature versus LO frequency for Receiver I. The IF bandwidth was DC-6 GHz.

We measured the gain and noise temperature of Receiver I across the IF passband by feeding the output of the JCA amplifier into an Agilent E4407B spectrum analyzer. The resolution bandwidth was set to 1 MHz, and power was integrated over 25 MHz. Figure 8 shows output power as a function of IF frequency for hot and cold terminations when the LO frequency is tuned to 225 GHz and 240 GHz. The power has a 5 - 10 dB ripple with ~ 1 GHz period at ν_{LO} = 225 GHz. While the IF power for ν_{LO} = 240 GHz is reasonably flat from 2 – 4 GHz, the noise temperatures $T_{rec,DSB}$ show a similar characteristic 1 GHz ripple across the 8 GHz IF band for both LO frequencies. $T_{rec,DSB}$

derived from these curves, shown in Figure 9, rises sharply below 0.7 GHz and above 8.5 GHz, denoting the edges of the sensitivity band. Clearly, the BIMA mixers can be modified to have at least a 4 GHz IF bandwidth. The 20 K ripples with 1 GHz period in receiver temperature are due



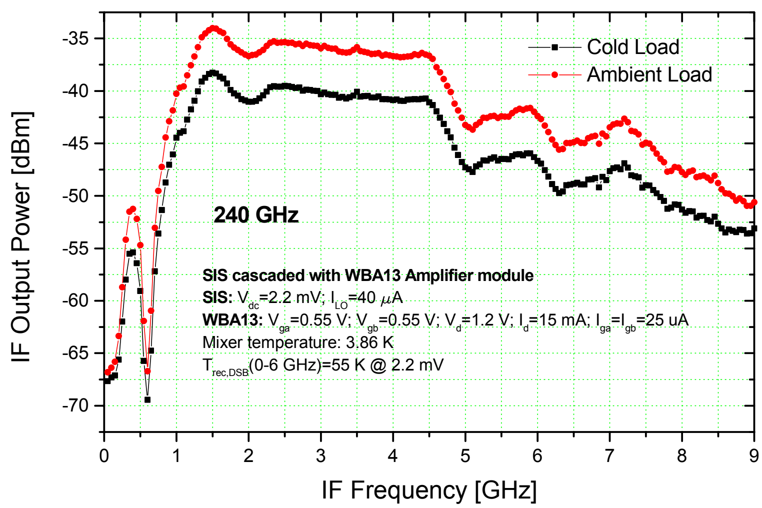


Figure 8 IF output power versus IF frequency for Receiver I at LO frequency of 225 GHz (top) and 240 GHz (bottom). Large ripples observed are due to impedance mismatch between the mixer and MMIC modules. These ripples become more severe for LO frequencies near the edges of the mixer RF band..

to a standing wave on the transmission lines linking the SIS junction to the WBA13 MMIC, indicating significant impedance mismatch. Even more severe ripples occur for $\nu_{LO} < 215$ GHz and

$\nu_{LO} > 245$ GHz. Such large gain and sensitivity variations in the IF passband would be difficult to calibrate out. In order to use Receiver I either the mixer needs to be followed by a wideband isolator; or a more sophisticated matching network is required; or mixer and MMIC need to be

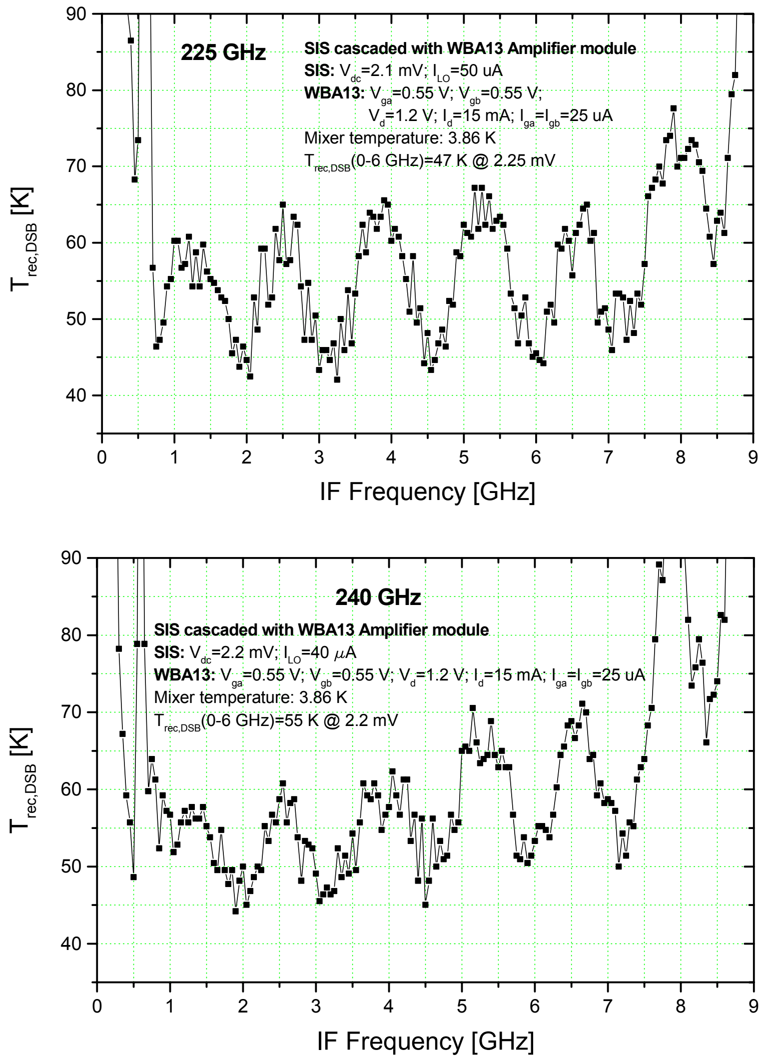


Figure 9 Receiver I narrow band noise temperature $T_{rec,DSB}$ measured as a function IF frequency for LO frequency of 225 GHz (top) and 240 GHz (bottom). Large ripples are due to an impedance mismatch between mixer and MMIC module.

electrically closer, which would increase the frequency interval of the standing wave and make passband calibration easier. Use of an isolator is the least desirable option since it would require increasing the IF band to 4-8 GHz; where commercially available devices operate; increasing the IF band would necessitate changing the OVRO mixers and the downconverter for the CARMA correlator. Elaborate matching networks can be lossy and are ultimately limited by the Fano Theorem[13].. Bringing mixer and MMIC electrically closer is perhaps the most desirable option. Receiver II, described below, is our first successful attempt at closely integrating mixer and MMIC.

(ii) Receiver II: SIS mixer integrated with WBA12 MMIC

We directly integrated a WBA12 amplifier (~25 dB gain) into a modified BIMA mixer block. Figure 10 shows an open view of the SIS/MMIC module and a closeup view of the circuitry linking the SIS mixer and InP MMIC amplifier.

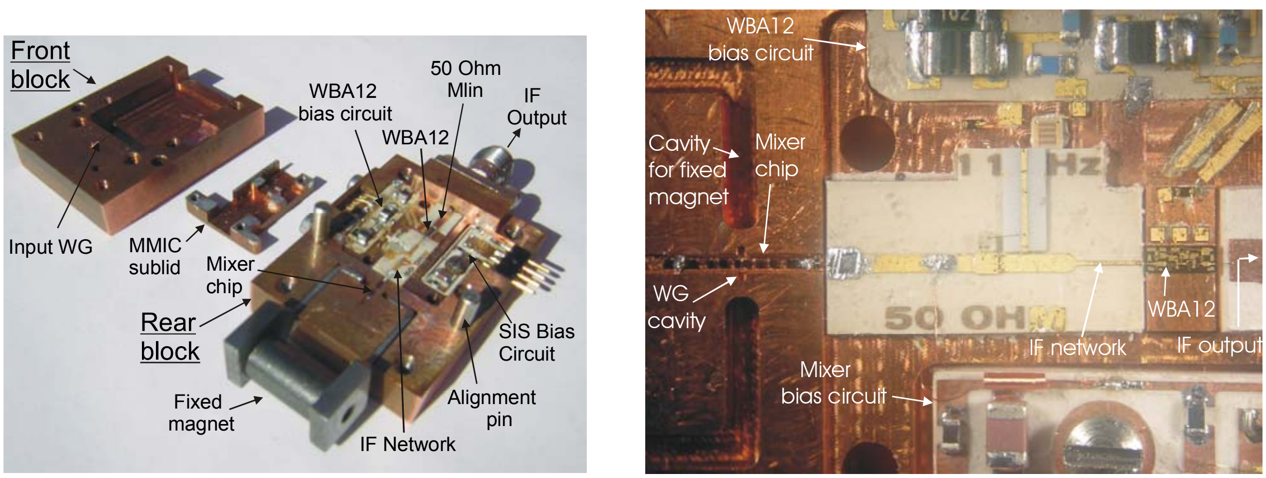


Figure 10 Open view of Rcceiver II showing SIS junction integrated with WBA 12 amplifier chip(left). Matching network shown in detail (right) presents 50 Ω to junction and 100 Ω to MMIC input gate.

Integration required installing a bias circuit for the MMIC, which supplies two independent gate voltages and a shared drain current for the HEMT stages. Dielectric Labs bias network chips (p/n B28BHBFNO1) filter radio frequency interference from the SIS bias lines; lumped element low pass filters protect the DC lines on the MMIC bias board. The IF network connecting the SIS chip and MMIC is fabricated on 15 mil thick Duroid 6002 (εr=2.93). The MMIC gate capacitance is tuned by a narrow (inductive) microstrip line followed by a ~6 mm long microstrip. This couples through a Dielectric Labs 6.8 pF capacitor to a short 50 Ω pad wirebonded to the output of the SIS chip. The IF network should present a 50 Ω impedance to the mixer chip IF port.. An irregularly shaped sublid, attached to the module body with 0-80 screws, encloses the matching circuit and MMIC in a rectangular waveguide with cutoff frequency above the maximum operating frequency of the amplifier. This should prevent the MMIC output signal from coupling back to the input. Feedback can lead to out of band oscillations which will degrade the gain stability and noise temperature of the receiver.

We originally assembled Receiver II with a WBA13 chip (~35 dB gain) but found that we could not prevent the MMIC from oscillating at 4 K, perhaps due to imperfect mechanical contacts or design of the sublid with the mixer module that may have caused unwanted coupling of the output of the MMIC to its input. The reduced gain of the WBA12 chip, combined with a modification of the IF network , and an improved mechanical design of the sublid, allowed us to stably bias the MMIC when cold. But the decreased gain made it necessary to follow with a wideband amplifier on the 10 K stage -- the coaxial WBA13 module -- in order to achieve desired receiver noise temperatures. These are shown plotted as a function of LO frequency in Figure 11. Receiver II performs well from 210 – 230 GHz, achieving noise temperatures as low as 43 K, but $T_{rec,DSB}$ rises steeply above 240 GHz. Since the SIS chip is identical for Receivers I and II it seems plausible that the reduced RF bandwidth is due either to misalignment of the chip in the suspended substrate channel, thereby reducing the bandwidth of the waveguide probe, or to an impedance mismatch between mixer and MMIC. Figure 12 shows that the IF power of Receiver II rolls off more smoothly with frequency than that of Receiver I. The effect of standing waves on sensitivity variation versus IF frequency has been reduced. However, when ν_{LO} = 225 GHz two standing waves appear superposed in gain and sensitivity– one with a period of 6 GHz and an amplitude of 15 K, and a second with the same

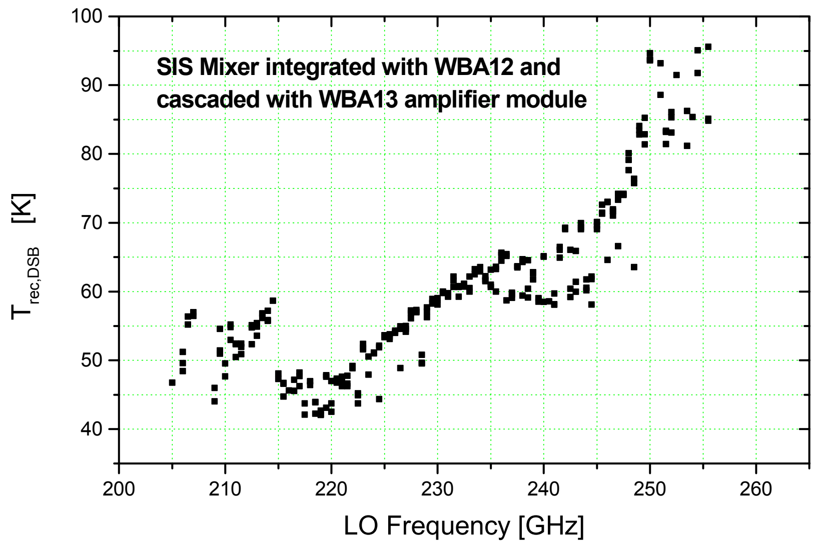


Figure 11 Receiver temperature of Receiver II as a function of LO frequency.. The sharply rising receiver temperatures for LO frequency > 230 GHz is possibly due to SIS probe misalignment in suspended stripline channel.

out at the spectrometer. The 6 GHz standing wave is likely due to mismatch between the SIS mixer and the WBA12 chip while the second faster period variation is probably due to a standing wave between the WBA12 and WBA13 amplifiers. It should be noted that the IF bandwidth of receiver II is 6 GHz while that of Receiver I is 8 GHz. Also, the wideband (6 GHz) noise temperature measurement for 225 GHz is 5 – 10 K lower than the average of the narrowband (25 MHz) results, which may be due to offsets in the spectrum analyzer.

A minor problem is the 20 mW power dissipated by the WBA12 amplifier which raises the SIS operating temperature ~0.7 K. This is likely to raise $T_{rec,DSB}$ less than 5 K. (see Figure 4).

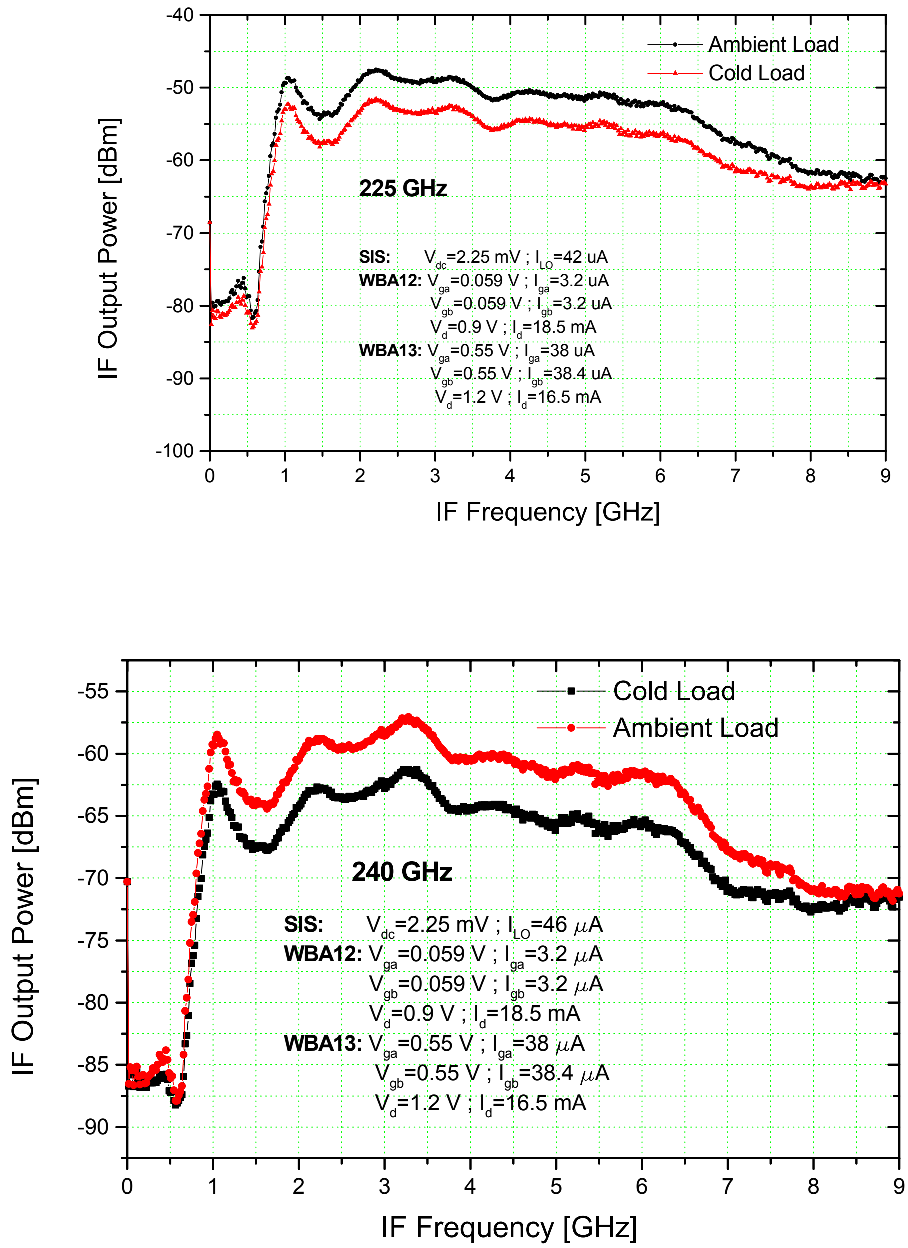
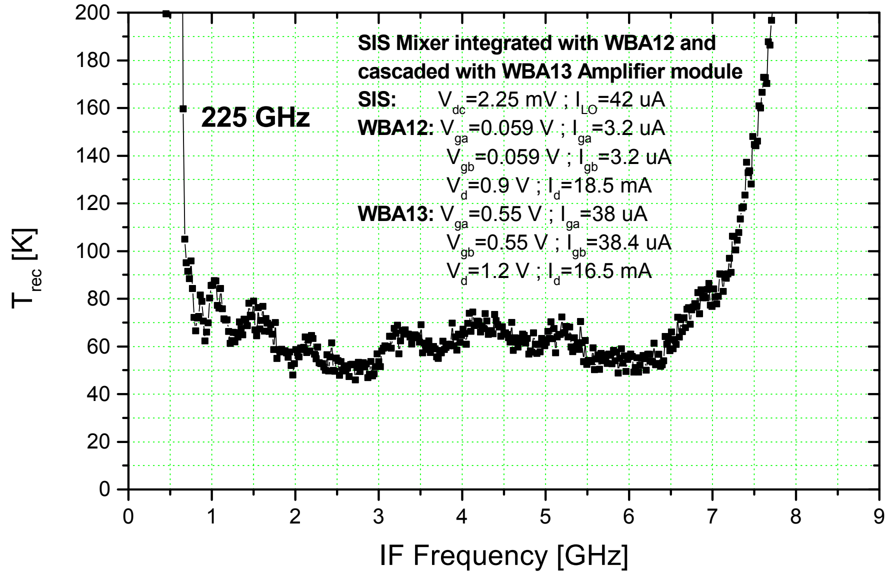


Figure 12 IF output power of Receiver II for LO frequency of 225 GHz (top) and 240 GHz (bottom). Ripples above 2 GHz significantly smaller than measured for Receiver I

period as that observed in the Receiver I IF band (1 GHz), but with 5 – 10 K amplitude. When ν_{LO} = 240 GHz, only the standing wave with 6 GHz period is evident, but a sharp resonance with 1 GHz bandwidth appears at 1.5 GHz. Overall, most of these gain variations should be possible to calibrate



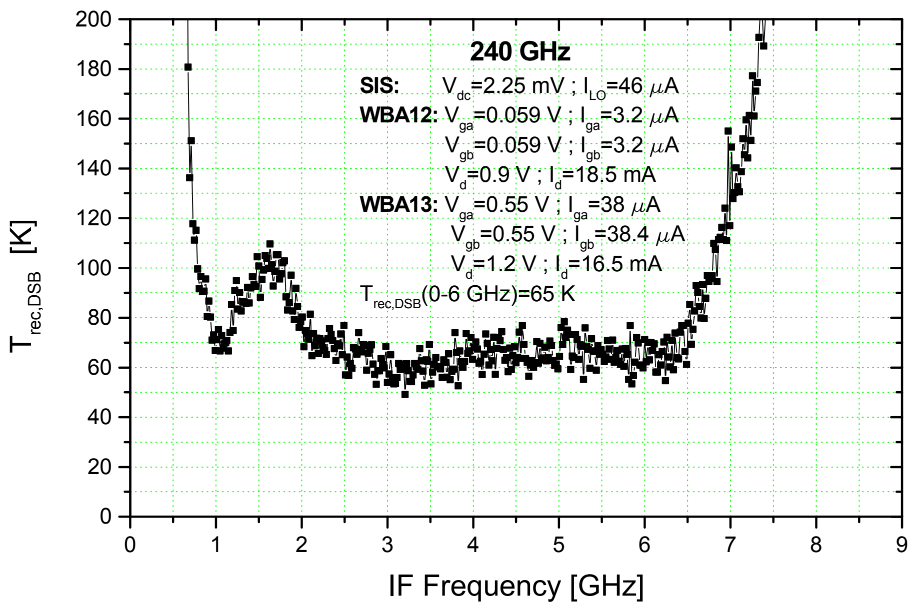


Figure 13 Receiver II narrow band noise temperature $T_{rec,DSB}$ measured as a function IF frequency for LO frequency of 225 GHz (top) and 240 GHz (bottom)..

(iii) Receiver III: Thermally split integrated SIS/WBA13 module

Our second attempt to integrate SIS device and MMIC, shown in Figure 14, involved radically altering the mixer module so that it has thermally independent stages for SIS and MMIC. A TeCu mixer block at 4 K supported by fiberglass tabs stands off 0.010” from an aluminum support block maintained at 10 K. From our experience, keeping the WBA13 chip at 10 K makes it easier to stably bias. And by thermally isolating the SIS junction we can maintain it at the lowest possible temperature for optimum sensitivity.

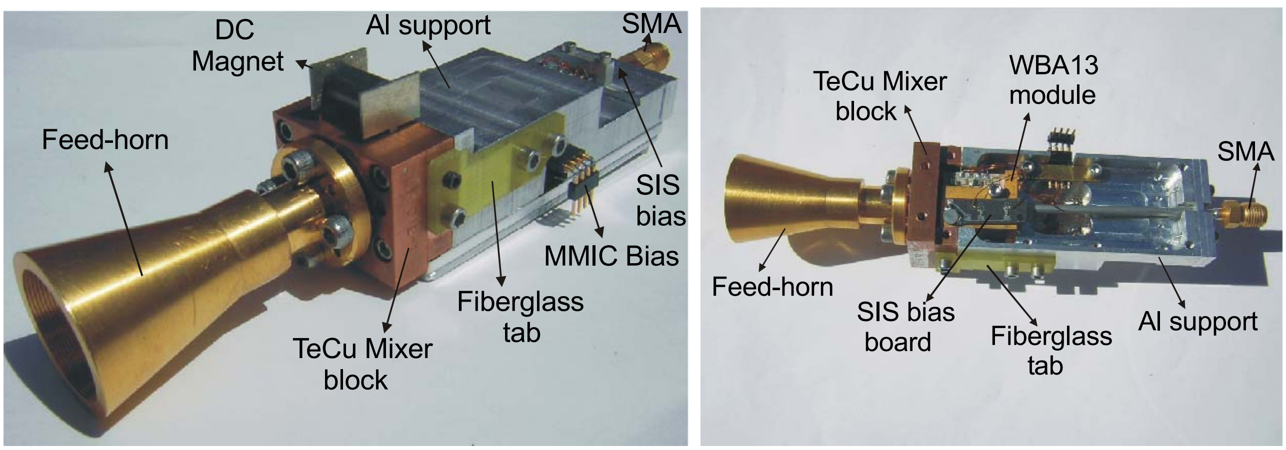


Figure 14 Receiver III assembled view (left) and open view (right). The TeCu mixer block at 4 K is thermally isolated from the WBA13 submodule at 10 K by fiberglass standoff tabs. A pair of 0.5 x 200 mil gold wires attach the mixer IF port to the 100 Ω input microstrip of the amplifier module.

The WBA13 MMIC is embedded in a submodule with bias circuitry; this submodule was designed and built by Wadefalk and Weinreb for the Allen Telescope Array front end[12]. The submodule is mounted in the support block with 2-56 screws. Two four-pin Microtech connectors supply bias to mixer and MMIC. The SIS bias board is attached to the top to the submodule and the DC bias attachment is made through a 10 turn inductor to the microstrip input of the MMIC submodule. The DC/IF port of the SIS mixer is connected by two 0.5 x 200 mil gold wires to the input of the MMIC module – the ground wire is soldered just below the open end of the suspended substrate SIS mixer channel and attaches to a point on the MMIC submodule just beneath the input microstrip.

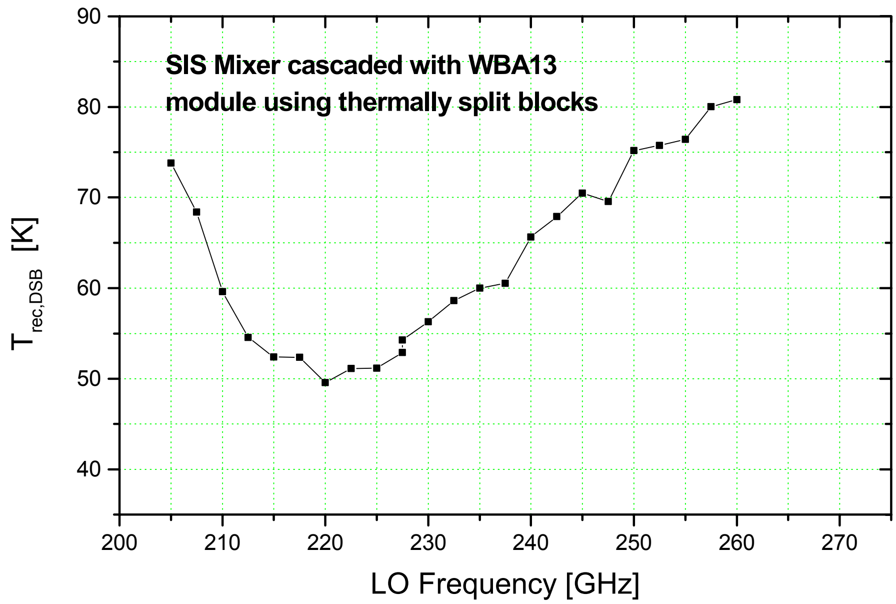
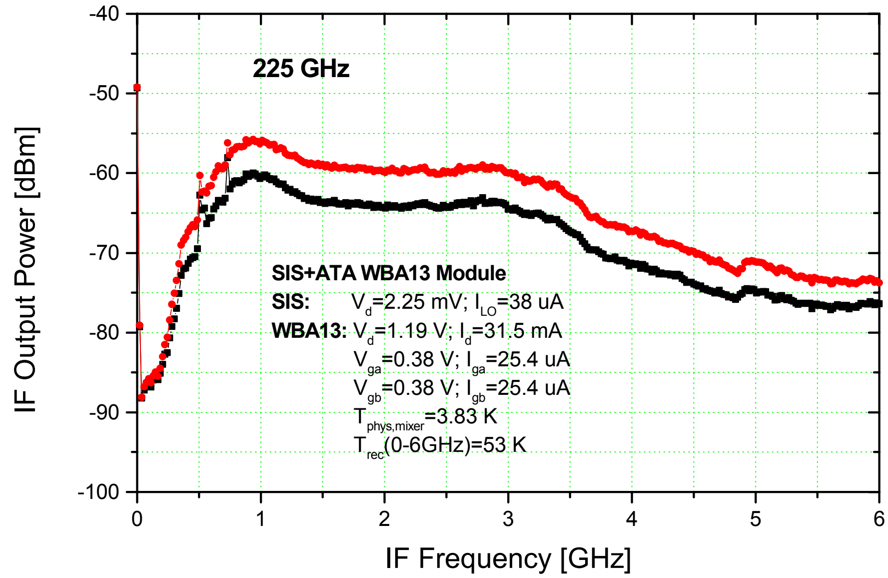


Figure 15 Integrated DC – 6 GHz receiver temperature measued for Receiver III for LO frequency range 205 – 260 GHz. Receiver temps. appear somewhat higher than Receiver I because the IF noise temperature rises above 4 GHz

Test results of Receiver III are encouraging. Figure 15 shows that the receiver temperature versus frequency characteristic is similar to that of Receiver I. Particularly striking is the smoothness of the receiver IF power curves shown in Figure 16. This is likely the combined result of close proximity of mixer and MMIC in addition to a different IF network in the WBA13 amplifier submodule, which presents a 100 Ω real impedance to the mixer. $T_{rec,DSB}$ as a function of ν_{IF} for ν_{LO} = 225 and 240 GHz are shown in Figure 17. IF gains are nearly flat for 0.5 – 4.5 GHz. Extension of the IF band to higher frequencies might be achieved by reducing the length of the signal and ground leads connecting mixer and MMIC. This would cause a slight increase in the operating temperature of the SIS mixer but in the current arrangement heat loading from the MMIC raises the mixer physical temperature only 0.1 K. For example, modelling shows that reducing the lead lengths from 200 mil to 20 mil could increase the IF bandwidth of Receiver III to that of Receiver II (6 GHz) while raising the integrated receiver temperature less than 5 K .



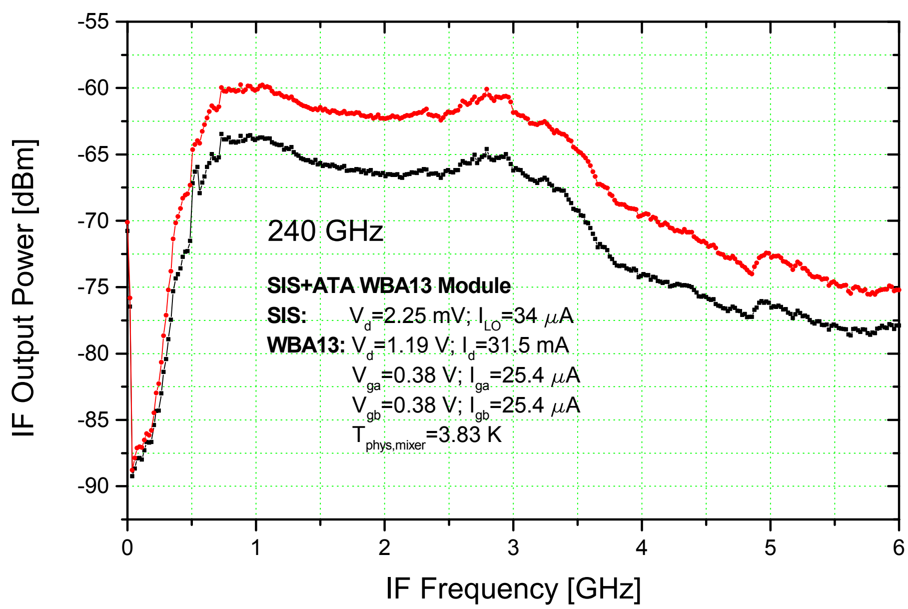
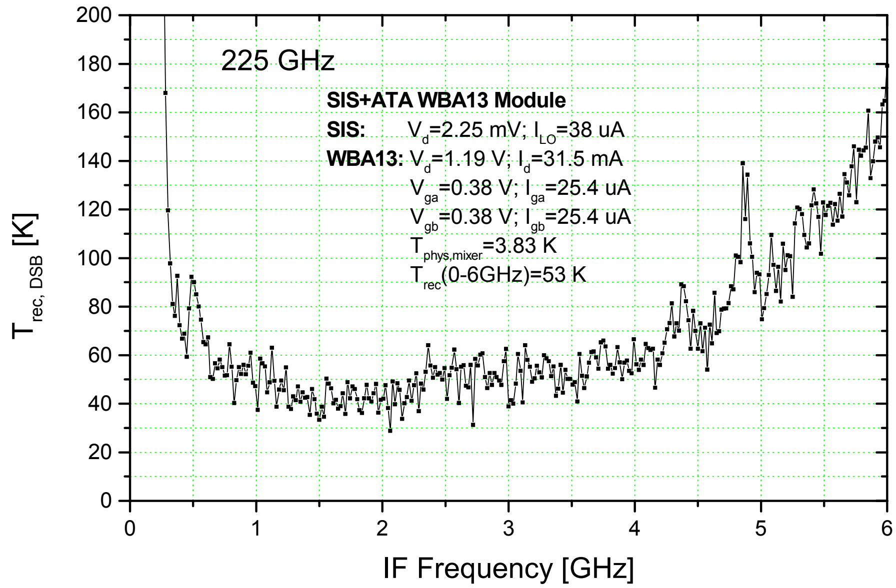


Figure 16 IF output power versus frequency for Receiver III for LO frequency 225 GHz (top) and 240 GHz (bottom).



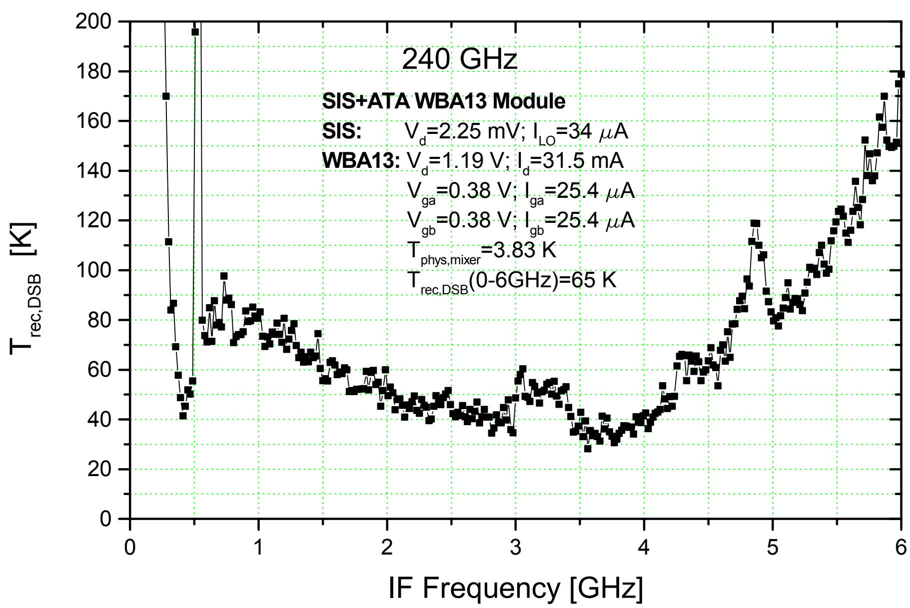


Figure 17 Receiver III narrowband (25 MHz) noise temperatures $T_{rec,DSB}$ measured as a function of IF frequency at a LO frequency of 225 GHz (top) and 240 GHz (bottom). This receiver has adequate sensitivity for CARMA and is compatible with the CARMA correlator.

5. SUMMARY

We attempted three schemes to broaden the IF bandwidth of the BIMA 1 mm receiver to match or exceed the 4 GHz bandwidth of the CARMA correlator, resulting in three receivers. For each receiver, noise temperature measurements for 205 – 270 GHz were made by measuring Y factors corresponding to IF power integrated from DC to 6 GHz. Also, variations in power and sensitivity across the IF band were measured at various LO frequencies. Receiver I was made by linking the BIMA SIS mixer module at 4 K to a 0.5 – 11 GHz MMIC amplifier module at 10 K (WBA13) with a 1" section of 50 Ω stainless steel coaxial cable. While the receiver temperatures across the RF band were satisfactory and the IF bandwidth was nearly 8 GHz, we measured ripple in receiver IF power arising from an impedance mismatch between mixer and MMIC that would be difficult to calibrate out. In receiver II we were able to decrease the frequency of this ripple by directly integrating a MMIC amplifier into a modified BIMA 1 mm mixer module. However, we had problems with stably biasing a WBA13 amplifier at 4 K, perhaps due to imperfect mechanical contacts or design of the sublid with the mixer module that may have caused unwanted coupling of the output of the MMIC to its input, so we substituted a lower gain MMIC chip, the WBA12 amplifier. The broadband noise temperatures across the RF band looked satisfactory for 210 -240 GHz, but a misalignment of the mixer chip may be the cause of the narrower measured overall RF bandwidth. The 20 mW of DC power supplied to the WBA12 device raised the SIS physical temperature only ~0.7 K but this is unlikely to have degraded $T_{rec,DSB}$ appreciably. Receiver III, based on a completely redesigned mixer module, maintains thermal isolation between the 4 K SIS junction and the 10 K WBA13 amplifier. Two 0.5 x 200 mil gold wires link the IF port of the SIS mixer to the100 Ω microstrip input of a WBA13 submodule embedded in the thermally split receiver module. Heat dissipation in the amplifier increased the physical temperature of the SIS junction only 0.1 K. $T_{rec,DSB}$ was satisfactory for LO frequencies of 205 – 260 GHz. Gain and sensitivity vary acceptably across the IF bandwidth of 0.5 – 4.5 GHz. Reducing the length of the gold leads connecting mixer and MMIC from 200 mil to 20 mil should increase the IF bandwidth to as much as 6 GHz without appreciably raising $T_{rec,DSB}$ across the band.

Of the three receiver schemes, we feel Receiver III shows the most promise for further development. In future efforts we will move the MMIC module even closer to the SIS mixer while maintaining the highest possible degree of thermal isolation and further optimizing the IF network in the MMIC submodule. Also, we plan to design and construct a thermally split mixer module for the SIS chip used in the NRAO 1 mm receivers realized for ALMA Band 6 (Kerr *et al.*[9]).

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