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A Wide-Band High-Gain Compact SIS Receiver utilizing a 300-μW SiGe IF LNA

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***Abstract*—Low-power low-noise amplifiers integrated with Superconductor-Insulator-Superconductor (SIS) mixers are required to enable implementation of large-scale focal plane arrays. In this work, a 220-GHz SIS mixer has been integrated with a high-gain broad-band low-power IF amplifier into a compact receiver module. The low noise amplifier (LNA) was specifically designed to match to the SIS output impedance and contributes less than 7 K to the system noise temperature over the 4-8 GHz IF frequency range. A receiver noise temperature of 30-45 K was measured for a local oscillator frequency of 220 GHz over an IF spanning 4-8 GHz. The LNA power dissipation was only 300 μW. To the best of the authors' knowledge, this is the lowest power consumption reported for a high-gain wide-band LNA directly integrated with an SIS mixer.**

***Index terms*—** Superconductor-Insulator-Superconductor (SIS) mixers, Heterodyne receivers, Cryogenic, Low noise amplifier (LNA), Focal plane arrays, Silicon-Germanium (SiGe)

I. INTRODUCTION

LARGE-SCALE heterodyne focal plane arrays (FPAs) are desired to enable wide-ranging sub-millimeter wave astronomical surveys, which will be used to study the stars, galaxies, and molecular clouds in the cosmos [1]–[3]. In comparison to today's state-of-the-art single-pixel THz instruments, a focal plane array containing hundreds or even thousands of pixels promises to provide a reduction of several orders of magnitude in the time it takes to acquire an image of a given fidelity. This is particularly important for ground-based sub-millimeter wave astronomy, as high system noise temperatures create a need for long dwell times, making large-scale surveys difficult, if not impossible, to carry out using a single pixel telescope. However, despite the promising science that might be done with such a system, THz heterodyne FPAs of this magnitude have been slow to develop due to the various mechanical and thermal challenges associated with their implementation [1].

Practical kilopixel heterodyne arrays will require sub-milliwatt power consumption low-noise amplifiers (LNAs) to enable cooling to liquid helium temperatures using commercial closed-cycle refrigerators. Silicon germanium (SiGe) LNAs have been recently emerged as a popular alternative to the HEMT IF amplifiers and particularly attractive due to their ability to operate with very low power consumption. A 2mW SiGe IF LNA with 16-dB gain suitable for direct connection to an SIS mixer was reported by Russell [4]. It was later shown that SiGe HBTs can be used to implement high performance cryogenic LNAs operating with sub-milliwatt power consumption [5]. A SiGe LNA with 10-dB gain and drawing just 100 μW of dc power and directly connected to an SIS mixer was later reported [6]. However, due to low gain of this amplifier, a second stage of cryogenic amplification was required to suppress the noise contribution of the warm IF network. Since this amplifier consumed 15 mW, the overall power consumed by the cryogenic electronics was still quite high. Demonstrating that a high performance receiver can be realized without requiring any high power cryogenic electronics is an important step towards scaling such systems towards the thousand-element level.

In this paper, the design and characterization of a low-power cryogenic LNA operating over more than an octave of IF bandwidth is presented. The amplifier provides sufficient gain so as to not require a second-stage cryogenic LNA in the receiver system. The outline of the paper is as follows:

1) The design and characterization of the SiGe LNA is described and results are compared to simulations.
2) The integration of the SiGe LNA with an SIS mixer is shown and the noise contribution of the IF network is measured using the SIS shot noise method.
3) The receiver performance is characterized over the desired frequency range and results are compared to the other state-of-the-art receivers.

II. IF LOW-NOISE AMPLIFIER DESIGN

A two-stage LNA was designed using the SiGe heterojunction bipolar transistor (HBT) models described in [5]. The SIS mixer selected for this work was a distributed series array of three SIS junctions previously reported in [7]. The IF impedance of the intrinsic SIS junction was modeled as a 150 Ω resistor in parallel with a 300 fF capacitor. The resistance value was measured using the DC $I-V$ curve of the SIS mixer. The equivalent junction capacitance was calculated from the geometry of the junctions and the microstrip tuning circuit at the center of the mixer chip. The embedding network of the SIS mixer was modeled using a full-wave electromagnetic simulator.

The amplifier was optimized to present the nominal performance when driven from the IF output impedance of the mixer. A schematic diagram of the LNA is shown in Fig.1. An

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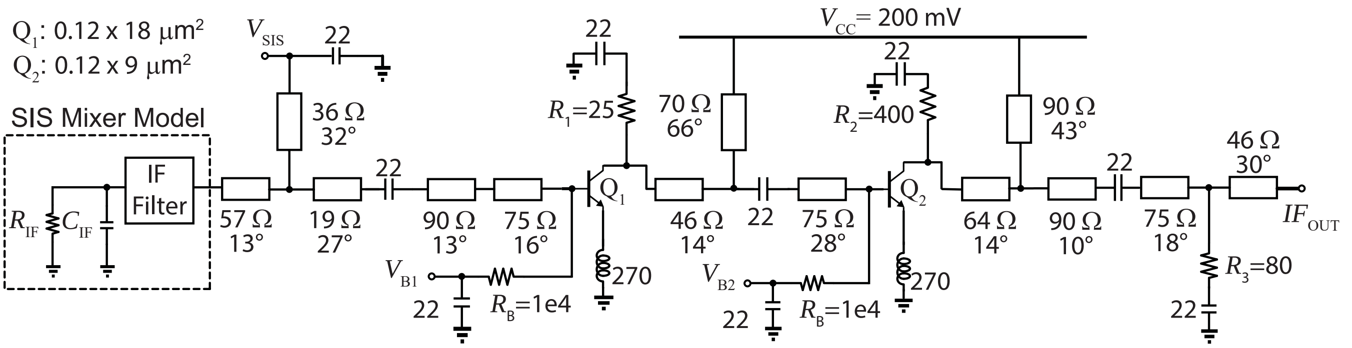

Fig. 1. Schamtic diagram of the amplifier. Electrical length is specified at 6 GHz. Units are as follows: Capacitors-pF, Resistance-Ohm, Inductance-pH.

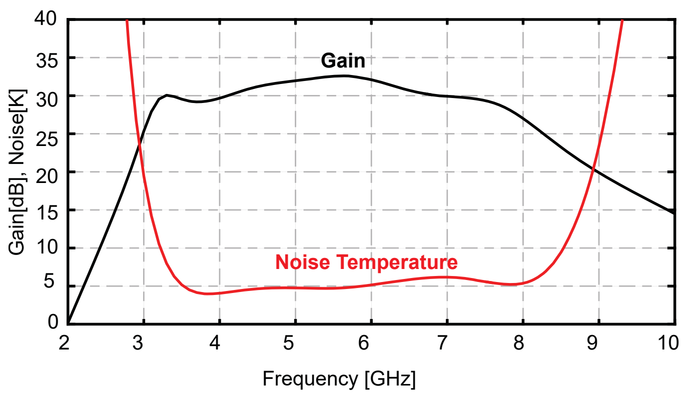

Fig. 2. Simulated noise and gain of the LNA driven from the SIS mixer equivalent model. The amplifier was biased at Ic_1=1.4 mA, Ic_2=1 mA, and Vcc=200 mV

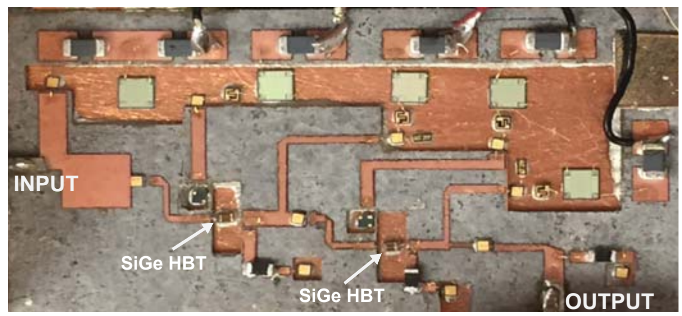

Fig. 3. A photograph of the assembled LNA circuit.

input matching network was included in the design to balance the noise with the input return loss. The transistors were inductively degenerated using bondwires to improve the input match. A shunt line in the input matching network was used to bring DC bias to the SIS junction. The inter-stage and output matching networks were designed to flatten the frequency response. Shunt resistors R_1, R_2, and R_3 were incorporated into the design to ensure stability. Bias was provided to the bases of the transistors through 10-kΩ resistors.

The amplifier was designed to provide 30 dB gain over the 4-8 GHz frequency range and less than 7 K noise temperature. The simulated noise temperature and gain of the LNA when driven from the equivalent circuit of the SIS mixer appear in Fig. 2. The LNA was designed to operate with DC base voltages of approximately 1.05 V and DC collector voltages between 150 and 400 mV. The DC current corresponding to this range of collector voltages varies from 2 to 2.4 mA.

III. Experimental Results

The LNA was assembled in a housing that was designed to mate with the SIS mixer block. A photograph of the assembled LNA circuit is shown in Fig.3. The printed circuit board was fabricated on a 0.25 mm thick RT/Duroid 6002 substrate of dimensions 13 mm by 26 mm. The amplifier was implemented using discrete transistors from the IBM BiCMOS8HP process [8] together with the wire bondable and surface mount resistors and capacitors. The SiGe transistors were mounted inside openings in the PCB board to facilitate wire bonding to chassis ground and RF lines. Ferrite beads were used on the DC lines to prevent any potential resonance between bypass capacitors.

A. *Verification of LNA Performance in a 50 Ω Environment*

Prior to integrating the LNA with the SIS mixer, the amplifier was charactrized in a 50 Ω environment. An SMA connector was mounted at the input of the LNA to facilitate measurements. The amplifier was mounted in a cryostat which is set up to support both scattering parameter measurements as well as noise temperature meausrements that are carried out using the cold attenuator method [9]. Noise, gain, and return loss measurements were carried out at 15 K physical temperature and results are in excellent agreement with simulation (Fig. 4). The 3 K difference between simulated noise and the measurement at 6 GHz is likely related to the discontinuity between the 50 Ω connector and the input line of the printed circuit board, which was not modeled.

B. *SIS-mixer/SiGe-LNA Receiver Performance*

Once characterization of the amplifier in a 50 Ω environment was complete, the SMA connector at the input of the LNA was removed and the amplifier module was bolted directly to an SIS mixer block. A photograph of the assembly appears in Fig. 5(a). The interconnect between the amplifier input and the SIS mixer chip was made using 0.125 mm wide, 1 mm long BeCu wire, which was soldered to the input of the amplifier. A pressure contact was made to the SIS mixer chip.

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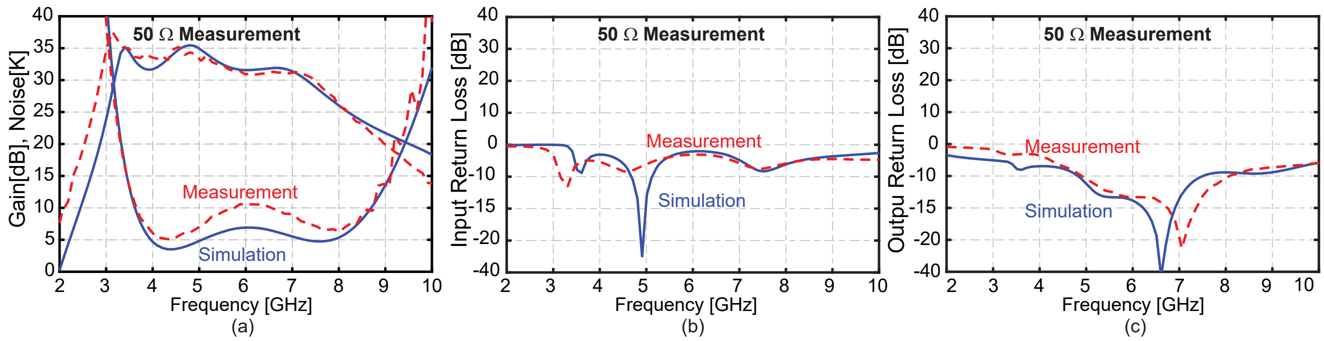

Fig. 4. LNA performance in a 50-Ω environment. Dashed lines are measurement results and solid lines are simulations. The amplifier was biased at Ic_1=1.4 mA, Ic_2=1 mA, and Vcc=200 mV (a) Gain and noise temperature at 15 K temperature. (b) Input return loss of the LNA at 50-Ω generator impedance. (c) Output return loss of the LNA.

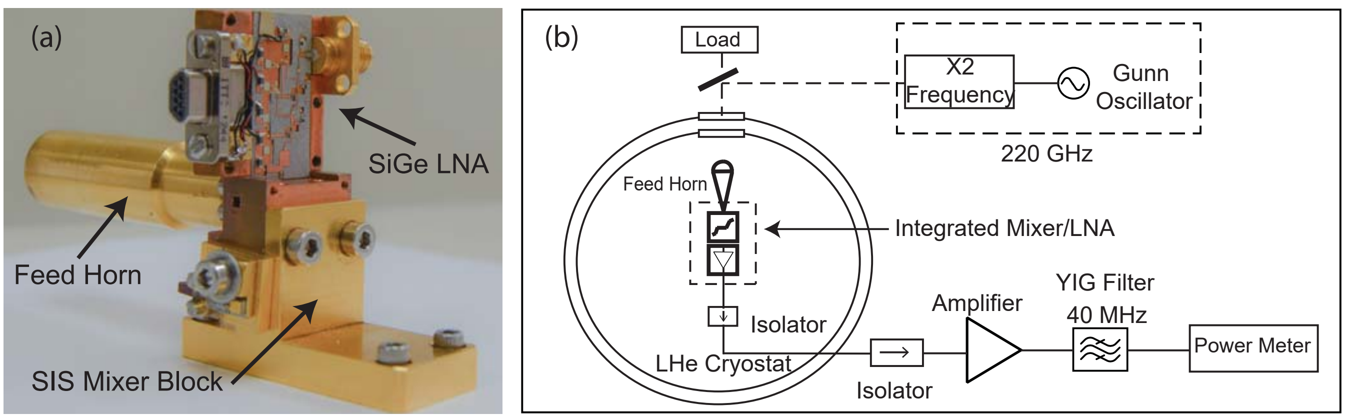

Fig. 5. (a) A photo of the LNA block directly connected to the Mixer block. (b) A block diagram of the measurement setup.

The hybrid assembly was mounted in a liquid helium cryostat configured to facilitate Y-factor measurements (see Fig. 5). A tunable local oscillator (LO) signal was generated using a frequency doubled Gunn oscillator. A wire grid polarizer was used as an LO coupler to combine the LO and signal beams. The combined beam was focused by a cold Teflon lens onto the corrugated feed horn of the SIS mixer block. The IF signal coming out of the cryostat was further amplified by a room temperature chain comprising of a 4-8 GHz isolator followed by a 0.1-12 GHz amplifier. This room temperature IF chain had a gain of approximately 40 dB and a noise temperature of 270 K.

To verify the LNA performance, the noise contribution of the IF network was characterized using the SIS mixer shot noise method [10]. The three junction mixer was biased above the gap at 12 mV to avoid quantum susceptance associated with the junctions and, at this bias, the differential resistance was found to be approximately 40 Ω. The IF noise was calculated from 4 to 8 GHz, in 1 GHz steps. The loss in the cryogenic cables and the room temperature IF chain was de-embedded. The measurement results are consistent with the predicted noise of the LNA when driven from a 40-Ω generator impedance (see Fig. 6).

Next, The DC operation of the SIS-mixer was characterized with the LNA biased at a DC power consumption of 300 μW. Fig.7 shows the unpumped $I-V$ curve of the mixer. No interaction between the SIS mixer and the LNA was observed

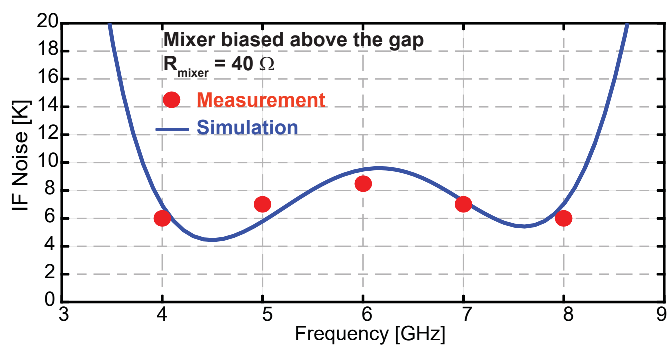

Fig. 6. The IF noise obtained from the shot noise experiment compared to simulation. The LNA was biased at Ic_1=1.2 mA, Ic_2=0.8 mA, and Vcc=150 mV.

in the DC characteristics of the SIS mixer.

The RF performance of the mixer was then measured by applying a 220 GHz LO pump power to the SIS junctions while the IF LNA was biased at a DC power consumption of 300 μW. Fig.7 shows the output power at an IF frequency of 4 GHz for ambient and liquid nitrogen loads. The peak output power was observed near the center of the photon step, which occurred at a bias voltage of approximately 7 mV. The double-sideband (DSB) receiver noise temperature was computed from Y-factor data for IF frequencies from 3 to 9 GHz and results are shown in Fig. 8(a). The noise temperature was

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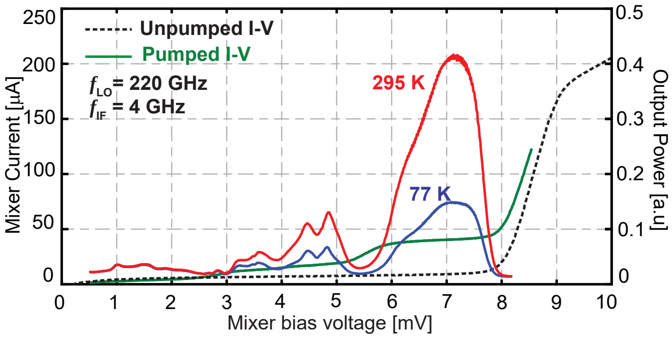

Fig. 7. The SIS mixer DC and RF charactristics. The dashed line shows the unpumped I-V curve and the green solid line shows the pumped I-V curve with a 220 GHz LO signal. The hot and cold load measurement was carried out using a room temperature and liquid nitrogen load. The LNA was biased at Ic_1=1.2 mA, Ic_2=0.8 mA, and Vcc=150 mV.

found to be between 30 and 40 K for the most of 4–8 GHz IF frequency range. While consuming only 300μW DC power, the SIS-mixer/SiGe-LNA receiver provides a system noise temperature within 5 K of baseline results obtained using the same mixer in a standard configuration[1].

Next, the impact of IF amplifier power consumption on system performance was evaluated. The DC power consumption of the LNA was swept from 660 μW down to 230 μW by changing the collector voltage. Minimal changes to the bias currents were observed over this range of collector voltages. As shown in Fig. 8(a), a marginal increase in the system noise temperature was observed for power levels as low as 230 μW.

Finally, the performance of the hybrid SIS-mixer/SiGe-LNA assembly was characterized as a function of LO frequency. For these measurements, the LO was swept from 212 to 232 GHz and Y-factors were recorded at IF frequencies of 4, 6, and 8 GHz. The results appear in Fig.8(b) and indicate that the noise temperature varies by approximately ± 5 K over this band.

C. Comparison to State of the Art

The improvement in measurement time that may be achieved using an FPA can be determined by considering number of pixels and the bandwidth and sensitivity of each pixel in comparison to that of a single pixel receiver. A metric which may be used to evaluate the scalability of a single pixel is $\alpha = B_{\text{MHz}}/T_{SYS}\,(P_{LNA,\,mW} + P_{IF\,cable,\,mW})$, where B_{MHz} is the IF bandwidth in MHz, T_{SYS} is the system noise temperature and includes the antenna noise temperature, $P_{LNA,\,mW}$ is the power consumption of the IF LNA in mW, and $P_{IF\,cable,\,mW}$ is the power consumption in mW associated with cooling the IF cable. This metric is appropriate for comparison of different results since it quantifies the ratio of integration time to overall DC power consumption.

The performance of the integrated SIS-Mixer/SiGe-LNA module is compared to other published results in Table I. Assuming an antenna temperature of 25 K and 600 μW for

[1]Baseline results were obtained using a cryogenic low noise amplifier (LNF416C) which consumed 15 mW of DC power. This amplifier was connected to the same mixer used in this study through an isolator.

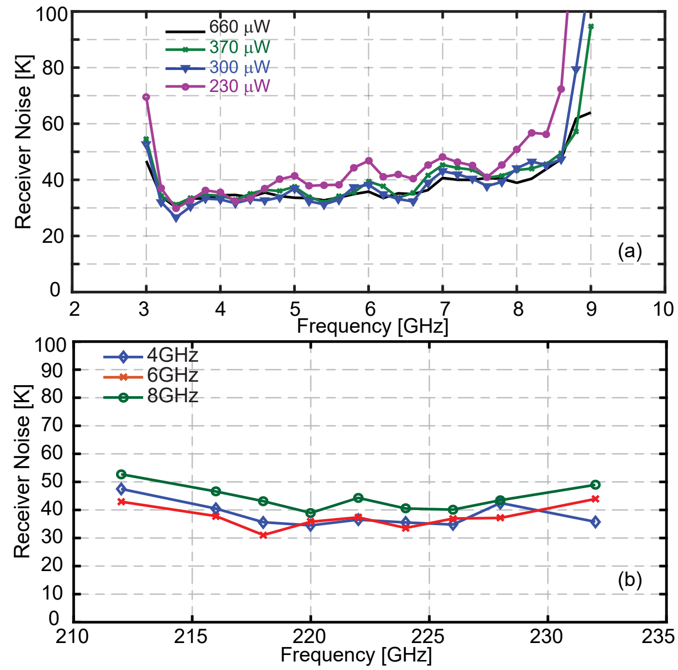

Fig. 8. Receiver performance when LNA was biased at Ic_1=1.2 mA, Ic_2=0.8 mA, and Vcc=150 mV which corresponds to 300 μW DC power. (a) Double side-band system noise temperature of the low power SiGe-LNA/Mixer at f_{LO}= 220 GHz at different power levels for the LNA. (b) Receiver noise temerature over the range of 212-232 GHz local oscillator frequency and IF spot frequencies of 4, 6, and 8 GHz.

TABLE I
STATE-OF-THE-ART SIS RECEIVERS

	T_{RX} K	BW MHz	$LNAP_{DC}$ mW	G dB	α $MHz/mW \cdot K^2$
[12]	75	2000	8	32	~ 0.023
[13]	16-20	6000	7.7	35	~ 0.39
[14]	43	6000	20	25	~ 0.063
[15]	45-57	8000	8.2	30-35	~ 0.16
This work	27-47	5500	0.3	30	~ 1.6

$P_{IF\,cable,\,mW}$ [11], α was computed for each of the results. The value of 1.6 MHz/K^{2}mW reported here is four times higher than the next best result. Thus, the results presented in this work represent a significant step forward in terms of developing the technology required to make scaled THz focal plane arrays practical.

IV. Conclusions

The results presented here demonstrate a broadband compact SIS receiver, with the lowest DC power dissipation reported to date. This is an important step towards scaling THz focal plane arrays to the kilopixel level. Future work should include the development of MMIC based ultra-low-power cryogenic LNAs designed to interface directly with SIS mixers.

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