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Cryogenic operation of a millimeter-wave SiGe BiCMOS low-noise amplifier

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***Abstract*—In this letter, we report the design and characterization of a cryogenically cooled Silicon Germanium (SiGe) low noise amplifier (LNA) covering a frequency range from 50 to 70 GHz. The amplifier was fabricated in 0.13-µm SiGe BiCMOS technology. At 20 K, the LNA showed stable operation, and an average noise figure (NF) of 2.2 dB (191 K) in the 52-65 GHz frequency band. This means 4.4 times improvement compared to the noise temperature at room temperature conditions for the same frequency band. When biased to lowest noise operation at cryogenic conditions of 20 K, the measured small signal gain was 18.5 dB at 60 GHz, while the consumed power was 6.3 mW, According to the authors' knowledge, this is the first report on cryogenic millimeter-wave SiGe low-noise amplifier and the lowest NF measured for a SiGe LNA in the 50-70 GHz frequency range.**

***Index Terms*—Cryogenic, low noise amplifier (LNA), silicon germanium (SiGe), noise, monolithic microwave integrated circuit (MMIC).**

I. Introduction

APPLICATIONS such as radio astronomy and remote sensing rely on cryogenic cooling systems to improve the sensitivity of their receivers. The state-of-the-art in this type of receivers incorporates low noise amplifiers (LNAs) developed using indium-phosphide (InP) high electron mobility transistor (HEMT) technology [1]-[4]. This type of technology has historically dominated the field of extreme low noise amplification, especially at cryogenic temperatures [5], [6].

In the last decade, silicon-germanium (SiGe) heterojunction bipolar transistors (HBT) have demonstrated excellent RF performance, including noise temperature (T_N), under cryogenic conditions [7], [8]. Moreover, it has been shown that it is possible to operate them at temperatures as low as 70 mK [9]. This has converted the SiGe HBT into a competitive alternative to InP HEMTs for the design of cryogenic RF LNAs. At low RF frequencies, the first cryogenic SiGe LNAs have shown T_N below 16 K in the range of 0.1 to 5 GHz [10] and from 1 to 6 GHz [11]. In addition, [12] presents a cryogenic SiGe LNA for the 15-25 GHz band, which is known so far as the highest frequency cryogenic SiGe LNA, showing also excellent T_N, with values below 35 K.

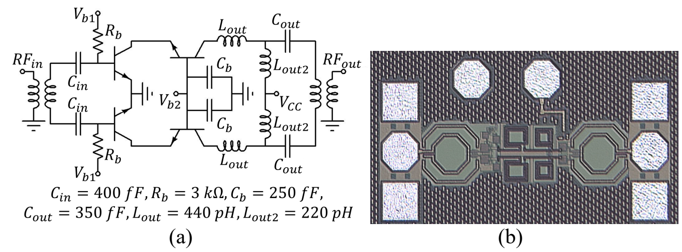

Fig. 1. (a) Simplified schematic of the LNA. The bias network is not shown for simplicity. (b) Micrograph of the LNA. The chip size is 620 um x 325 µm including pads.

In this letter we report the cryogenic operation of a SiGe low-noise amplifier at millimeter-wave frequencies for the first time. Moreover, we study whether the cryogenic noise performance is adequate for utilizing the SiGe amplifier as a second amplification stage for a radio astronomy receiver front end where the receiver NF would be determined by the preceding HEMT MMIC low-noise amplifier (see [2] for InP amplifier performance). The possibility to integrate more functions on the same silicon chip would relax system hardware complexity inside the cryogenic Dewar for future generation of large arrays with hundreds of elements.

II. Circuit Design

The LNA was designed in IHP's 0.13 µm SiGe BiCMOS technology with f_T/f_{max} of 250/340 GHz. Simplified schematic and micrograph of the LNA are shown in Fig. 1. A one-stage amplifier was designed in differential cascode configuration with inductors as an output load. It should be noted that there was no cryogenic transistor model available at the time of the LNA design. Differential configuration was chosen because of our future aim of integrating the amplifier with a differential mixer. Furthermore, on-chip transformers are used to convert the differential mode to single-ended mode and to ease the on-wafer measurements in a 50-Ω environment. The

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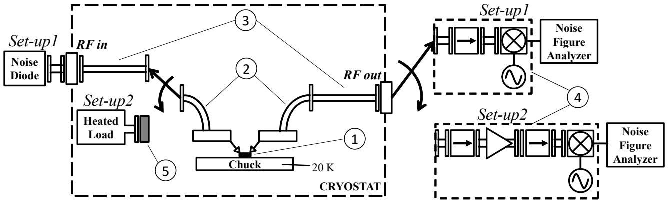

Fig. 2. Diagrams of two noise figure set-ups: *Set-up1* uses a noise diode and *Set-up2* uses a heated load, as noise sources. (1) Device under test, (2) WR-15 probes, (3) WR-15 waveguide set, (4) down-conversion block and (5) WR-15 thermal insulator.

simulated loss of one transformer is around 0.8 dB at room temperature. Emitter degeneration was not used in the amplifier design in order not to decrease the gain of the single-stage cascode LNA. The device size for the common emitter (A_E=6×0.12×0.14 μm^2) and common base (A_E=6×0.12×0.08 μm^2) transistors were selected carefully to achieve optimum noise match with a reasonable input matching. To have a good and well-controlled RF ground return current path we plan to use flip-chip connection for the LNA chip. Thus, the input matching was designed to resonate out ground-signal-ground flip-chip bumps when connecting the amplifier to a PCB substrate. This will lead to somewhat poor input match when the amplifier is measured on-wafer. The amplifier is biased using on-chip current mirrors.

III. Measurements

A commercial cryogenic probe station was used for the on-wafer measurements presented in this work (Nagase, BCT-21MRFZ). Fig. 2 shows a diagram with the component set-up internal to the cryostat; *Set-up1* was used to perform automated NF measurements with a noise-diode, while *Set-up2* was a verification set-up for measurements at 20 K using heatable load inside the cryostat as a noise source. In the *Set-up1* the RF measurement signals are routed into the device under test (DUT) and out from the probe station through a pair of symmetric waveguides. The waveguides and the probe tips are not connected to the cryogenic cooling system. The noise diode (Millitech, model NSS-15-R1520) was used to provide the hot and cold temperatures involved in the Y-factor method. The excess noise ratio (ENR) of the noise source was previously measured in-house, and its value is in the range of 13.9-17.6 dB for the 50-70 GHz frequency band. In both set-ups, a down-converter block (DCB) was connected to provide intermediate frequencies (IFs) to the noise figure analyzer (NFA, Agilent, model N8973A). The calibration of the NF measurements was done as follows. The NF of the DCB was measured by connecting it directly to the noise diode and then routing its output directly to the NFA. The measured value for the DCB was in the range of 4.4-6.5 dB over the 50-70 GHz band. The loss at temperature from the waveguides producing noise in the system, is considered equal for both signal arms including the waveguides and a probe. The loss for each arm, over the band of 50-70 GHz, was in the range of 1.7-2.7 dB at room temperature and 1.5-2.4 dB at 20 K. At both temperatures, the loss was measured using a 200 um long coplanar waveguide 'through' calibration standard, to connect the input and output probes. The physical temperature of the

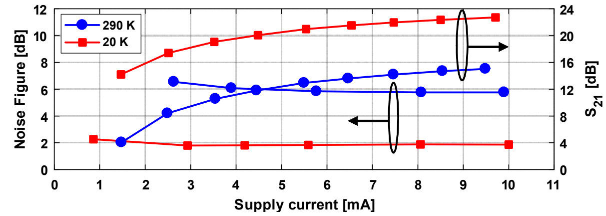

Fig. 3. Measured noise figure (using *Set-up1*) and S_{21} at room temperature and 20 K for 60 GHz as a function of the supply current. The supply voltage was in the range of 1.7 to 2.47 V.

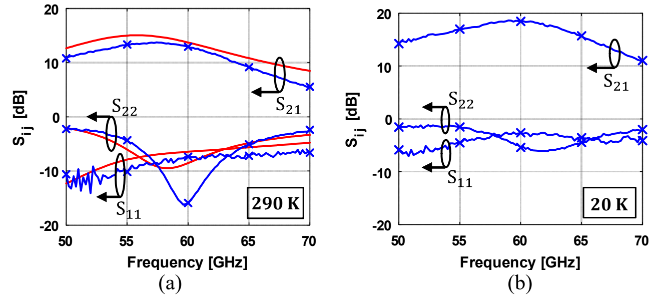

Fig. 4. S-parameters of the amplifier. (a) Simulated (solid lines) and measured (solid lines with crosses) at 290 K. The bias point was 2 V @ 5.5 mA. (b) Measured at 20 K. The bias point was 2.1 V @ 3 mA.

probes was measured using sensors attached to them.

In the case of *Set-up2*, the NF of the DCB was measured including the RF output probe plus waveguide, by means of the referred 'through' standard. The measured NF for the DCB was in the range of 6.75-9.25 dB over the 50-70 GHz band, accounting for an input probe loss of 0.7 dB, and that both probes were connected to a second cooling stage of the cryogenic system to 50 K. The cold and hot temperatures for the heated load used in this set-up were 50 and 170 K, respectively. To obtain the T_N of the DUT, the Y-factor method was used as in [14], and hence the noise derived gain extracted.

The S-parameters of the samples are measured connecting the RF input and output of the cryostat to a vector network analyzer (VNA, HP, model 85109), using the access waveguides shown in *Set-up1*. The system includes millimeter wave converters to extend the frequency range of the measurement setup to cover the range of interest. The VNA is calibrated inside the cryostat using on-wafer LRRM calibration [13].

The stability of the amplifier was studied at 20 K ambient. A Precision Semiconductor Parameter Analyzer (Agilent 4156C) was used to measure the current-voltage curve of the amplifier by sweeping the supply voltage from 0 to 2.5 V. This curve does not show sudden changes in the supply current at 20 K. In addition, a spectrum analyzer measured, from DC to 50 GHz, the spectral content of the system directly connected at the RF output of the probe station. No signs of narrowband spikes nor sudden changes in bias where observed at 20 K. Both tests confirm the stability of the LNA at these conditions.

Fig. 3 shows the results at room temperature and 20 K for the NF and gain measurements, at 60 GHz, as a function of supply current. At room temperature, it is observed that the optimum bias point for NF starts around 6 mA and is

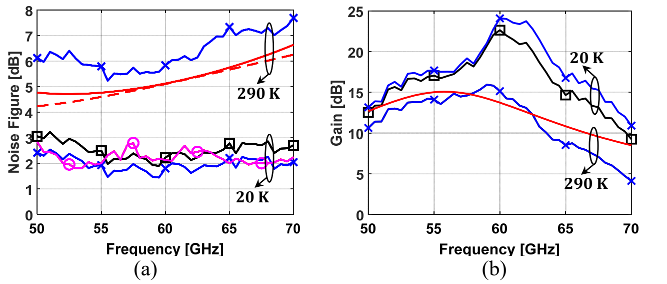

Fig. 5. Noise figure and derived gain of the amplifier at 290 and 20 K. (a) Noise figure. At 290 K: simulated (solid lined), simulated minimum NF (dashed line) and measured (solid line with crosses) using a noise diode as noise source. At 20 K: two samples measured using a noise diode as noise source (solid line with boxes and solid line with crosses) and one sample measured using a heated load as noise source (solid line with circles). (b) Derived gain. At 290 K: simulated (solid line) and measured (solid line with crosses). At 20 K: two samples measured using a noise diode as noise source (solid line with boxes and solid line with crosses). For both (a) and (b), the bias point used at 290 K was 2 V @ 5.77 mA and at 20 K was 2.1 V @ 3 mA.

maintained until 10 mA, with a nominal value close to 6 dB. At 20 K, it is observed that the optimum bias point for NF starts around 3 mA and is maintained until 10 mA. The nominal value for the NF in this range is approximately 1.8 dB, which can be explored with a dissipated power ranging from 6.3 mW to 24 mW. The lower power operational regime is attractive for systems that require many amplifiers to operate, but have limited cooling capacity.

Fig. 4 shows the S-parameters measured and simulated at room temperature and measured at 20 K. At room temperature, the measurements of the gain for a supply current of 5.5 mA reached a maximum value of 13.7 dB at 57.4 GHz. In general, the measured S-parameters are in fairly good agreement with the simulations. At 20 K, it is observed that gain reached a maximum value of 18.6 dB at 59 GHz, for a supply current of 3 mA (2.1 V supply voltage). The return losses have changed with respect to their values at room temperature. This is due to the fact that the transconductance of the transistor increases at cryogenic temperatures with a change in small-signal model associated capacitances and resistors as discussed in [8], and also due to the possibility to decrease the supply current for low noise.

The room temperature and 20 K measurements for NF and derived gain are shown together with the room temperature NF simulations, in Fig. 5. Over the measured frequency range at room temperature, and for a supply current of 5.77 mA, the DUT NF was in the range of 5.2-7.7 dB. At 20 K, the NF reached a minimum value of 1.4 dB at 59.5 GHz, for a supply current of 3 mA. As it can be seen from Fig. 5b, the results of the NF measurements of the amplifier using both set-ups are consistent with each other. The measured 1-dB output compression point (OP1dB) of the amplifier at 20 K is -0.54 dBm.

IV. Conclusion

We presented the design and characterization of a SiGe LNA for the 50-70 GHz band. We show, for the first time, cryogenic performance for a SiGe LNA in this frequency range. The results of the amplifier characterization at 20 K are summarized in Table 1 and compared with the state-of-the-art from the literature.

TABLE I
Comparison with Cryogenic Noise Performance of State-of-the-Art SiGe LNAs

Ref.	Temp. [K]	Bandwidth [GHz]	T_N [K]	Gain [dB]	P_{DC} [mW]
[10]	15	0.1-5	4.3*	>29.6	20
[11]	19	0.5-4	<8	>25	8.3
[12]	15	19-23.5	≤45	>20	<0.9
This Work	**20**	**52-65**	**191***	**>15.6**	**6.3**

*Average.

The amplifier, when cryogenically cooled to 20 K, reached an average NF of 2.2 dB (191 K) in the 52-65 GHz frequency band, this means that the T_N at 20 K ambient is 4.4 times less than at room temperature for the same frequency band.

Finally, the amplifier consumed 6.3 mW at the optimal cryogenic bias point, which is 1.8 times lower than at room temperature. According to the authors' knowledge, this is the lowest NF measured for a SiGe LNA in the 50-70 GHz band. The achieved NF is adequate for utilizing the amplifier as a second amplifier stage in a cryogenic radio astronomy receiver. However, future work is needed for optimizing the LNA performance using a cryogenic transistor model.

References

[1] Mikko Varonen et al., "An MMIC low-noise amplifier design technique," IEEE Trans. Microw. Theory and Techn., vol. 64, no. 3, pp. 826-835, Mar. 2016.
[2] Mikko Varonen et al., “Cryogenic MMIC low-noise amplifiers for V-band,” in IEEE MTT-S Int. Microw. Symp, Honololu, HI, 2017, pp. 172-175.
[3] Matthew Sieth et al., "Argus: a 16-pixel millimeter-wave spectrometer for the Green Bank Telescope." in Proc. SPIE mm, Sub-mm, and Far-IR Detectors and Instr. for Astro. VII, Montréal, Canada, Jul. 2014, Vol. 9153, pp. 1-12.
[4] David Cuadrado-Calle et al., "Broadband MMIC LNAs for ALMA Band 2+3 With Noise Temperature Below 28 K," IEEE Trans. Microw. Theory and Techn., vol. 65, no. 5, pp. 1589-1597, May. 2017.
[5] M. W. Pospieszalski, "Extremely low-noise amplification with cryogenic FETs and HFETs: 1970-2004," IEEE Microwave Magazine, vol. 6, no. 3, pp. 62-75, Sept. 2005.
[6] J. Schleeh et al., "Ultralow-Power Cryogenic InP HEMT With Minimum Noise Temperature of 1 K at 6 GHz," IEEE Electron Device Letters, vol. 33, no. 5, pp. 664-666, May. 2012.
[7] Partha S. Chakraborty et al., "A 0.8 THz fMAX SiGe HBT Operating at 4.3 K," IEEE Electron Device Letters, vol. 35, no. 2, pp. 151-153, Feb. 2014.
[8] J. C. Bardin and S. Weinreb, "Experimental cryogenic modeling and noise of SiGe HBTs," in IEEE MTT-S Int. Microw. Symp. Dig. Atlanta, GA, USA, Sept. 2008, pp. 459-462.
[9] Hanbin Ying et al., "Operation of SiGe HBTs Down to 70 mK," IEEE Electron Device Letters, vol. 38, no. 1, pp. 12-15, Jan. 2017.
[10] J. C. Bardin and S. Weinreb, "A 0.1–5 GHz Cryogenic SiGe MMIC LNA," IEEE Microw. Wireless Compon. Lett., vol. 19, no. 6, pp. 407-409, Jun. 2009.
[11] D. Russell and S. Weinreb, "Low-Power Very Low-Noise Cryogenic SiGe IF Amplifiers for Terahertz Mixer Receivers," IEEE Trans. Microw. Theory and Techn., vol. 60, no. 6, pp. 1641-1648, Jun. 2012.
[12] W. T. Wong , P. Ravindran, Su-Wei Chang and J. C. Bardin, "A SiGe Ka-band cryogenic low-noise amplifier," in IEEE MTT-S Int. Microw. Symp., San Francisco, CA, USA, Aug. 2016. pp. 1-3.
[13] A. Davidson, K. Jones and E. Strid, "LRM and LRRM Calibrations with Automatic Determination of Load Inductance," in 36th ARFTG Conf. Digest, Monterey, CA, USA, Mar. 1990. pp. 57-63.
[14] D. Russell, K. Cleary, and R. Reeves, “Cryogenic probe station for on-wafer characterization of electrical devices,” Rev. Sci. Instrum 83, 044703, pp. 1-10, Apr. 2012.