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## Cryogenic Operation of a Millimeter-Wave SiGe BiCMOS Low-Noise Amplifier

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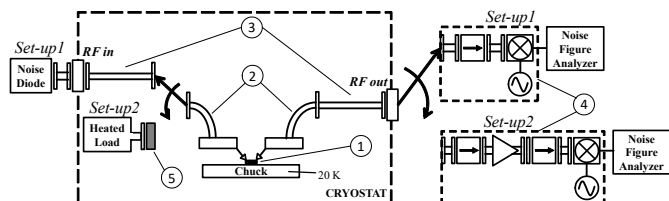


Fig. 2. Diagrams of two noise figure set-ups: *Set-up1* uses a noise diode and *Set-up2* uses a heated load, as noise sources. (1) Device under test, (2) WR-15 probes, (3) WR-15 waveguide set, (4) down-conversion block and (5) WR-15 thermal insulator.

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 ( $A_E=6\times 0.12\times 0.14\ \mu\text{m}^2$ ) and common base ( $A_E=6\times 0.12\times 0.08\ \mu\text{m}^2$ ) 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  $\mu\text{m}$  long coplanar waveguide ‘through’ calibration standard, to connect the input and output probes. The physical temperature of the

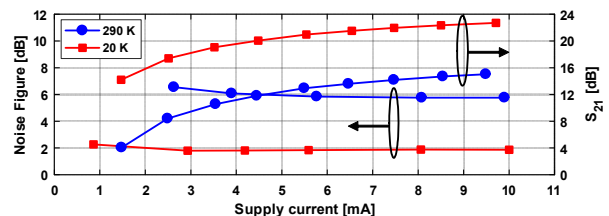


Fig. 3. Measured noise figure (using *Set-up1*) and  $S_{21}$  at room temperature and 20 K for 60 GHz as a function of the supply current. The supply voltage was in the range of 1.7 to 2.47 V.

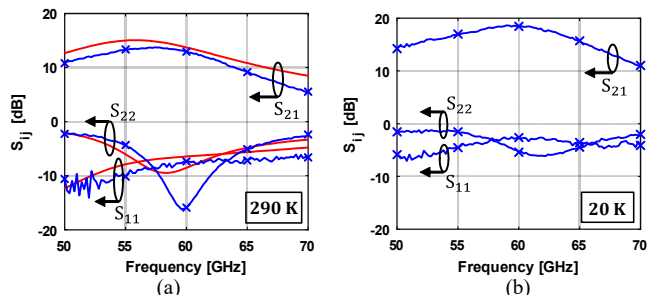


Fig. 4. S-parameters of the amplifier. (a) Simulated (solid lines) and measured (solid lines with crosses) at 290 K. The bias point was 2 V @ 5.5 mA. (b) Measured at 20 K. The bias point was 2.1 V @ 3 mA.

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 were 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

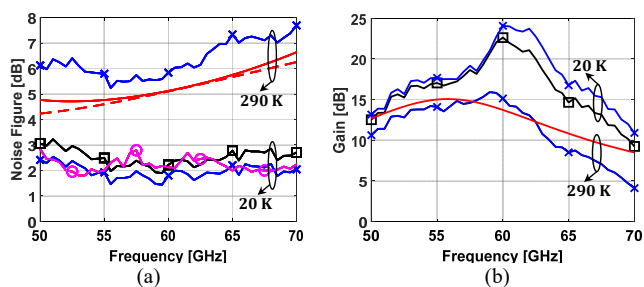


Fig. 5. Noise figure and derived gain of the amplifier at 290 and 20 K. (a) Noise figure. At 290 K: simulated (solid lined), simulated minimum NF (dashed line) and measured (solid line with crosses) using a noise diode as noise source. At 20 K: two samples measured using a noise diode as noise source (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

TABLE I  
COMPARISON WITH CRYOGENIC NOISE PERFORMANCE OF  
STATE-OF-THE-ART SiGe LNAs

Ref.	Temp. [K]	Bandwidth [GHz]	$T_N$ [K]	Gain [dB]	$P_{bc}$ [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
<b>This Work</b>	<b>20</b>	<b>52-65</b>	<b>191*</b>	<b>&gt;15.6</b>	<b>6.3</b>

\*Average.

summarized in Table 1 and compared with the state-of-the-art from the literature.

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.

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