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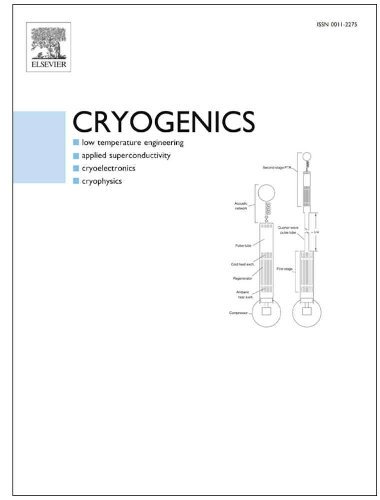

Research paper

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Cryogenic performance of a 3-14 GHz Bipolar SiGe Low-Noise Amplifier

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Abstract

The performance of silicon-germanium (SiGe) transistors under cryogenic operation is analyzed. The design and characterization of a 3-14 GHz low-noise amplifier (LNA) using SiGe transistors at 300 K and at 13 K are presented. A three stage amplifier is implemented with bipolar transistors model BFU910F from NXP commercially available with a plastic package. The amplifier exhibits 36.8 dB average gain with average noise temperature of 103 K and 42 mW DC power consumption at 300 K ambient temperature. Whereas cooled down to 13 K ambient temperature, it provides 32.4 dB average gain, 11.4 K average noise temperature with a minimum of 7.2 K at 3.5 GHz and a DC power dissipation of 5.8 mW. The presented LNA demonstrates an outstanding performance at cryogenic temperature for a commercial plastic packaged transistor.

Keywords: Low-noise amplifier (LNA), cryogenic, Silicon-Germanium (SiGe), bipolar transistor

1. Introduction

Cyogenic low-noise amplifiers are of great interest due to applications such as large radio astronomy receivers, space communications, high sensitivity systems for physic research, or quantum computing. Among these applications, the scalability of terahertz superconductor-insulator-superconductor (SIS) based systems has motivated the development of intermediate frequency (IF) LNAs with ultra-low power consumption. In that range of intermediate frequencies, there has been a great effort in the development of cryogenic low-noise amplifiers over the last years, which have shown the best performance in terms of noise temperature, as low as 4 K, using technologies based on high-electron mobility transistors (HEMT) such as indium phosphide (InP) HEMT[1-5]. Other technologies, like gallium arsenide (GaAs) metamorphic HEMT [6] and more recently silicon-germanium (SiGe) heterojunction bipolar transistors (HBT), have also demonstrated outstanding noise performance in those frequency bands [7 – 15]. One important characteristic of these IF amplifiers is their low power dissipation, which is of great importance for cooling systems with a large number of receivers, as in high sensitivity experiments. Among the most recent works presented in the literature on the design of cryogenically cooled low-noise amplifiers, those based on SiGe technology have demonstrated noise temperatures below 10 K with DC power consumption of hundreds of microwats as in works [12-13]. One of the best noise performance SiGe cryogenic amplifiers has shown a noise temperature of 2.8 K with an associated gain of 22 dB from 0.3 to 3 GHz [16]. For higher frequencies a recent work [12] describes a 4 to 8 GHz SiGe amplifier showing 26 dB of gain with lower than 1.5 dB of noise figure at ambient temperature and noise equivalent temperature of 8 K working at 15 K ambient temperature with an ultralow power consumption. These results try to compete with the best cryogenic performances up to now at those frequencies with technologies such as InP HEMT or GaAs HEMT.

In this work the performance of a broadband LNA based on a plastic packaged SiGe transistor from 3 to 14 GHz at cryogenic temperatures is presented. This paper is organized as follows: DC characterization and analysis of the SiGe transistor at different temperatures are presented in Section 2. The design and manufacturing of the low-noise amplifier are described in Section 3. Measurement results at 300 K and 13 K are presented in Section 4. Finally, conclusions extracted from this work are summarized in Section 5.

2. Cryogenic SiGe Technology

SiGe HBTs have arisen as a competitive alternative for designing cryogenic low-noise amplifiers. Some of the advantages of the SiGe cryogenic transistors, compared to the widely used cryogenic HEMTs, are the repeatability and high-yield of the process compatible with standard CMOS processes. On the other hand, cryogenically cooled SiGe transistors show better gain stability in comparison with HEMT devices [9], which restricts the last ones performance for some radio astronomy applications. In order to evaluate the SiGe transistors for low-noise amplification at cryogenic temperatures, their noise performance has been investigated in several works [17 – 20]. Noise performance in bipolar SiGe transistors is dominated by the thermal noise due to the base resistor and the shot noise caused by DC base and collector currents. The minimum noise temperature for a simplified noise model can be expressed as [20]:

$$T_{MIN} \approx n_c T_a \sqrt{\frac{1}{\beta_{DC}}(1+2D) + 2D\left(\frac{f}{f_t}\right)^2} \qquad (1)$$

$$D = \frac{g_m(r_b+r_e)}{n_c} \qquad (2)$$

where $n_c = I_C q/kT_a g_m$ is the collector current ideality factor, q is the electron charge, k is the Boltzmann's constant, T_a is the ambient temperature, $\beta_{DC} = I_C/I_B$ is the DC current gain (I_C collector current and I_B base current), g_m is the intrinsic transconductance, r_b and r_e are the base and emitter resistances respectively and f_T is the unity current gain cutoff frequency.

By cooling down the transistor at cryogenic temperatures, its noise performance improves significantly since the temperature is lower and the parameters β_{DC} (current gain), g_m and f_T increase [20], while the base resistance decreases [21] producing a negligible thermal noise. At low frequencies, the noise performance can be evaluated with a more simple expression of the minimum noise temperature written as

$$T_{MIN\_lf} \approx \frac{n_{cx}}{\sqrt{\beta_{DC}}} T_a \approx K_n T_a \qquad (3)$$

where $n_{cx} = I_c q/G_m k T_a$ is the extrinsic collector current ideality factor, and G_m is the extrinsic transconductance $G_m = g_m(1+g_m r_e)$.

In this work, the DC characteristics of the chosen SiGe transistor at different cryogenic temperatures are measured in order to analyse its performance and its low-frequency noise features. The evaluation of the constant K_n in (3) is used to assess the low-frequency noise performance of the SiGe transistor when it is cooled down.

2.1 BFU910 SiGe Transistor

A bipolar SiGe transistor is chosen for the design of the low-noise amplifier. The transistor model is BFU910 from NXP, which is a NPN wideband silicon germanium RF transistor with f_T of 90 GHz. This device is commercially available with low-cost plastic package, and for room temperature operation. The manufacturer provides a transistor model with noise parameters at room temperature. One possible disadvantage of using packaged transistors is its susceptibility to parasitic effects of the package, as well as a more difficult predictability of its performance when it is cryogenically cooled. On the other hand, these transistors could be prone to mechanical failures of the package while thermal cycling between cryogenic and ambient temperatures. The used transistor NXP BFU910 has not presented any failure during several performed thermal cycles showing all the tested devices successful electrical performance. The package has kept its structure safe without any defect after at least four performed cooling cycles between ambient and cryogenic temperatures. Somehow, this transistor allowed us to evaluate its plastic package under cryogenic operation. Previous published works have also demonstrated the behaviour of packaged SiGe transistors or other devices under cryogenic temperatures [22 – 25].

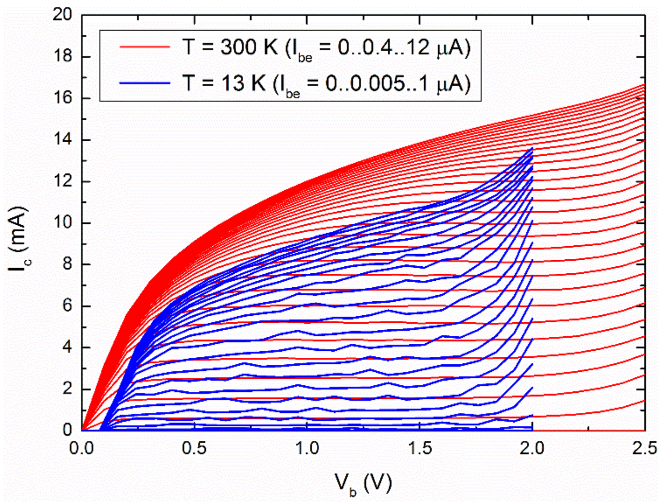

Fig. 1. Common-emitter output characteristics at 300 K and 13 K ambient temperature for 0.4 µA and 5 nA steps base-emitter current (I_{be}) respectively for the transistor BFU910 NXP.

DC measurements of the transistor are made with the Semiconductor Device Parameter Analyzer B1500A from Agilent Technologies and two external HP 11612A Bias Networks terminated with 50 Ω loads. The DC output characteristics of the transistor BFU910 are obtained with the emitter terminal tied to ground. Fig. 1 shows the collector current-voltage (I-V) characteristics at 300 K (red line) and 13 K (blue line) with base current as swept parameter. The transistor shows a good behaviour in its output features and a reduction of the breakdown voltage at 13 K.

In Fig. 2 the collector current is shown as a function of base-emitter voltages for V_{CB} = 0 V at five different ambient temperatures. The slope of the collector current increases with the base-emitter voltage at lower temperatures, since the transconductance (G_m) of the transistor increases. On the other hand, the threshold voltage increases from 0.67 V at 300 K to 0.95 V at 13 K when cooling down.

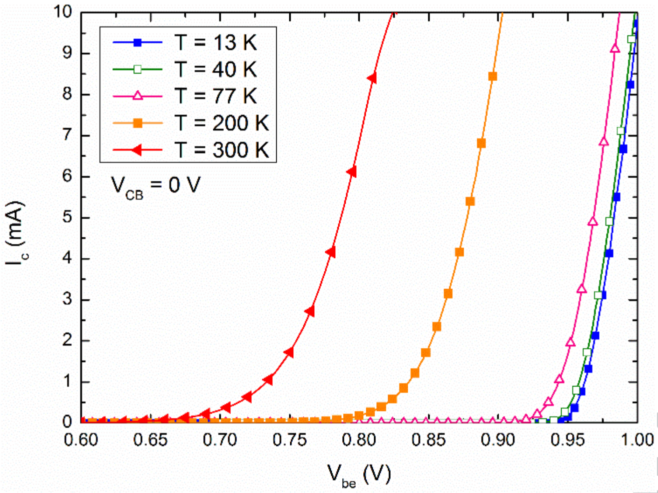

Fig. 2. Collector current as a function of base-emitter voltage at five ambient temperatures for the transistor BFU910 NXP.

DC measurements of the NXP BFU910 transistor current gain (β_{DC}) and transconductance (Gm) as function of collector current (I_C) are shown in Fig. 3 and Fig. 4 at five temperatures. Both β_{DC} and Gm increase by cooling from 300 to 13 K. β_{DC} has a maximum of 2200 with a collector current of 4.7 mA at 300 K and it increases by a factor of 3.67 (β_{DC} = 8082) at 13 K with 7.9 mA of collector current. On the other hand, for a collector current of 7.65 mA, Gm takes its highest value at 300 K (155 mS) and it increases by a factor of 2.16 from 300 K to 13 K (335 mS at 13 K and 11.5 mA collector current).

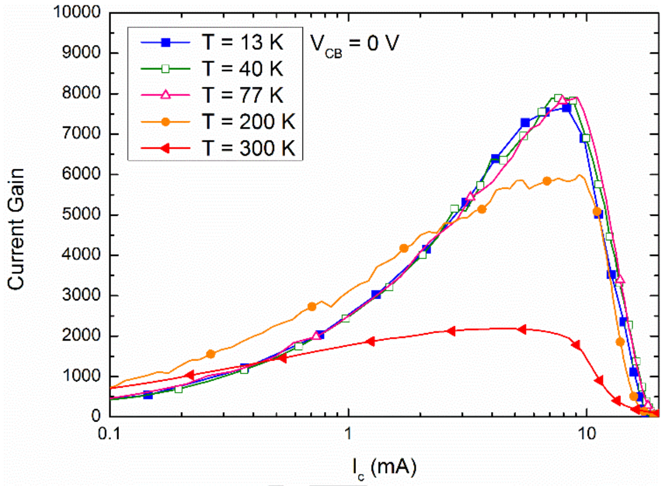

Fig. 3. Measured current gain ($\beta_{DC} = I_c/I_b$) versus collector current at several ambient temperatures with V_{CB} = 0 V for the transistor SiGe BFU910 NXP.

Using the values of the transistor current gain (β_{DC}) and transconductance (Gm) measured at different temperatures, the parameter K_n in (3) is calculated and it is depicted in Fig. 5. This parameter shows the dependence of the noise temperature of the transistor at low frequencies as a function of the collector current. At 13 K, the minimum K_n is less sensitive to the collector current and it occurs for lower currents than at 300 K. These DC measurements at cryogenic temperatures of the SiGe BFU910 NXP transistor can provide its collector current for optimum noise performance at low frequencies.

Measured s-parameters of the packaged SiGe transistor at room temperature (300 K) from 200 MHz up to 20 GHz are shown in Fig. 6.

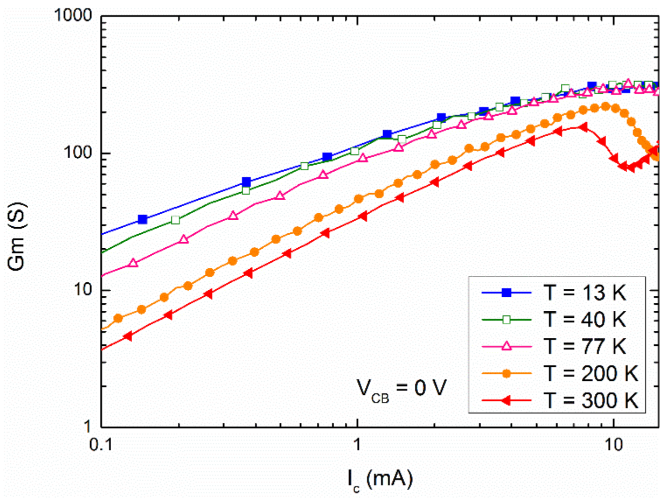

Fig. 4. Measured DC extrinsic transconductance ($\partial I_c/\partial V_{be}$) versus collector current at several ambient temperatures with VCB = 0 V for the transistor SiGe BFU910 NXP.

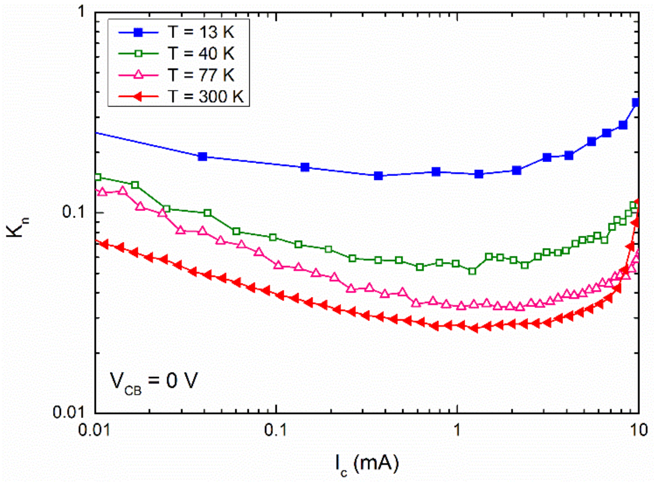

Fig. 5. Parameter $K_n = n_{cx}/\sqrt{\beta_{DC}}$ versus collector current at several ambient temperatures with V_{CB} = 0 V for the transistor SiGe BFU910 NXP.

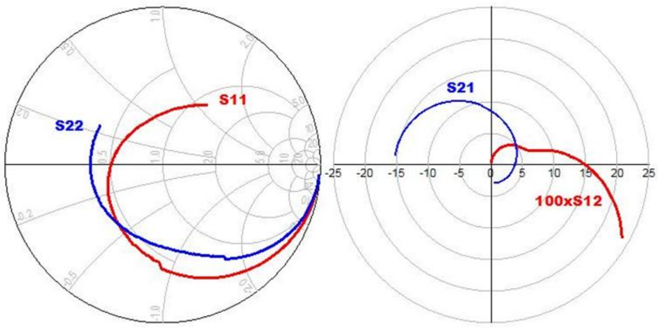

Fig. 6. Measured S-parameters at room temperature (300 K) for the transistor BFU910 NXP from 200 MHz to 20 GHz biased at V_{CE} = 2 V and I_{CE} = 7 mA.

3. Design of the Low-noise Amplifier

A 3-14 GHz low-noise amplifier is designed in microstrip technology. The LNA consists of three stages with three transistors NXP BFU910. A simplified schematic of the LNA is shown in Fig. 7.

The three stages are in common emitter configuration and each one can be individually biased. The design is optimized in order to obtain minimum noise temperature with flat gain over the operating bandwidth.

The reflection coefficient for minimum noise of the common emitter transistor without any additional emitter feedback, allows to obtain simultaneously low noise with high return loss. At low frequencies, the input impedances for minimum noise and low return loss are closer for SiGe transistors than for HEMT transistors.

The bias networks together with the interstage DC blocking capacitors provide flat gain response over the bandwidth. The base-bias circuits in the second and third stages consist of 1 kΩ (high value) resistor with a wide band performance. On the other hand, the first stage base-bias is made of a large inductance to minimize the noise impact.

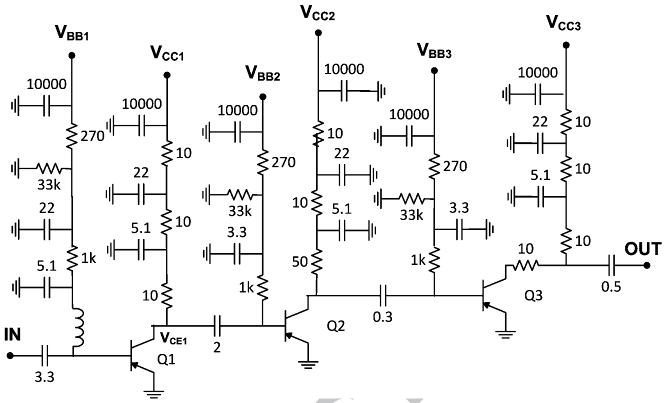

Fig. 7. Simplified schematic of thee-stage 4-12 GHz low-noise amplifier. The transistors Q1, Q2 and Q3 are BFU910. The units are: capacitors in pF and resistors in Ω.

Base bias networks contain a voltage divider 10:1 to avoid overvoltage. Both base and collector bias networks have 10 nF capacitors to provide a low impedance path to ground for AC components of the DC signal.

3.1 Amplifier Manufacturing

The three-stage microwave integrated circuit (MIC) amplifier is shown in Fig. 8. The amplifier was assembled in a test fixture with super SMA coaxial connectors. Microstrip lines of the amplifier are fabricated on a plastic substrate CLTE-XT with relative dielectric constant 2.94 and 10 mils thickness. The components used in the design were carefully selected based on previous measurements at cryogenic temperatures. The small variations with temperature of dielectric constants of capacitors and resistivity of the resistors were considered in the design. The resistors are thick film from State-of-the-Art (SOTA) based on tantalum-nitride, which have been widely used at cryogenic temperatures in hybrid low-noise amplifiers and with a change of only 3 % of the nominal resistance at 4 K [26]. The capacitors of 3.3 pF, 5.1 pF, 2pF, 0.5 pF and 0.3 pF are single layer devices from American Technical Ceramics (ATC) with a low dielectric constant material (value of 60 - type CA) in order to guarantee their appropriate performance under cryogenic temperatures, since they decrease in value around 6% cooling down to 4 K [26]. The 22 pF are metal-insulator-semiconductor (MIS) chip capacitors with silicon oxide-nitride dielectric from Skyworks, which also are suitable for stable operation at cryogenic temperatures. Moreover, the 10 nF capacitor in all the bias networks is a multilayer ceramic chip capacitor based on NP0 dielectric with good capacitance stability at temperatures lower than 20 K [25], [27 – 28]. The inductance in the schematic has been done through long gold bonding wires of 25 µm diameter. All the components and the substrate were glued to the chassis with EPO-TEK H20E conductive epoxy in order to assure a proper ground connection.

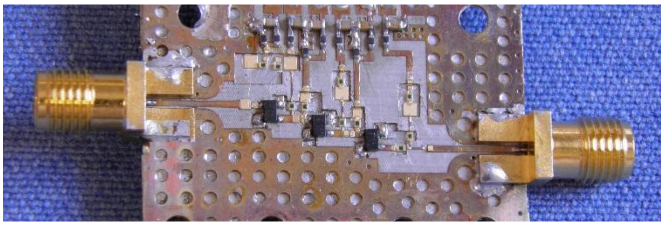

Fig. 8. Low-noise amplifier implemented in a module with SMA coaxial connectors. The circuit board is 6 mm x 3 mm with SMA coaxial connectors.

4. Experimental Results

The amplifier is characterized at both 300 K and 13 K ambient temperatures. At 300 K Scattering parameters and noise figure are measured, while at 13 K gain and noise temperature are obtained. At 300 K the amplifier is biased with $V_{CC} = 2$ V supply voltage with a collector current of 7 mA per stage, while the amplifier cooled down to 13 K is biased with a supply voltage around 2 times lower as well as a total collector current 3 times lower in order to obtain the best noise temperature.

4.1 Ambient Temperature (300 K)

The measured and simulated Scattering parameters of the LNA at 300 K are depicted in Fig. 9, showing an accurate fit between them. The amplifier achieves an average gain of 35.9 dB in the band from 3 to 14 GHz. The total power consumption is 42 mW. The amplifier presents loss in band input return better than 5 dB from over the band, which is an important parameter for systems where a SIS mixer is used in order to avoid the use of an isolator [29].

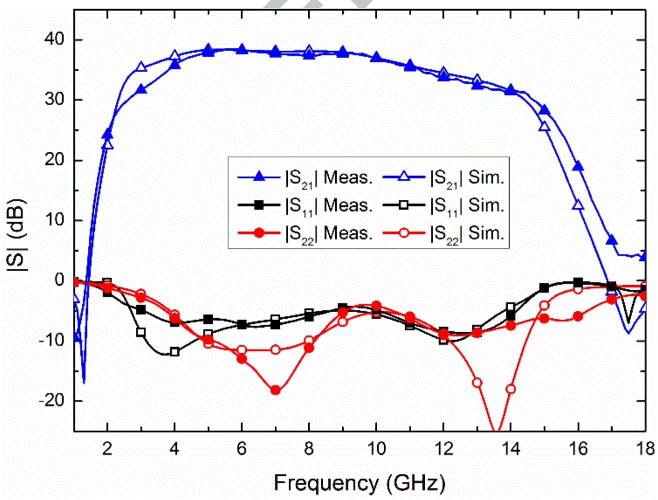

Fig. 9. Amplifier scattering parameters, measurement and simulation at 300 K room temperature with supply voltage $V_{CC} = 2$ V and total $I_{CE} = 21$ mA.

The measured and simulated gain and noise temperature of the amplifier at 300 K are shown in Fig. 10. The optimum bias point for low noise is a supply voltage $V_{CC} = 2$ V and a collector-emitter current $I_{CE} = 21$ mA. The amplifier exhibits a gain of 36.9 ± 4.3 dB and average noise temperature of 103 K (noise figure of 1.32 dB) within the band, with a minimum noise temperature of 71 K at 4 GHz. The average noise temperature from 4 to 8 GHz is 81 K (noise figure of 1.07 dB).

4.2 Cryogenic Temperature (13 K)

The noise temperature and the gain of the amplifier working at 13 K ambient temperature is measured inside a cryostat. The cryogenic system employed is based on the Gifford-McMahon cooling cycle. The system uses Helium gas as refrigerator to reach such low extreme temperatures, and it is composed of two stages. The cooling system is a DE-210AE from Advanced Research Systems (ARS), providing a cooling power of 60 W at 77 K on its first stage and 4 W at 10 K on its second stage. The dewar is made of aluminium and it is designed to keep a vacuum better than 10^{-6} mbar. The tested circuits are attached to a second stage base connected to the cold-head, in which a minimum temperature of 9 K is achievable. Moreover, phase-stable stainless steel coaxial cables with 1.85 mm connectors are used to connect the device-under-test (DUT) to the feedthrough connectors in the cryostat walls. They were previously characterized at cryogenic temperature in order to obtain their performance at the operating temperature. The sensors are Lakeshore DT-670 series silicon diodes with good accuracy over a wider temperature range. A Lakeshore 340 temperature controller with several temperature sensors is used to control and measure the temperatures inside the cryostat.

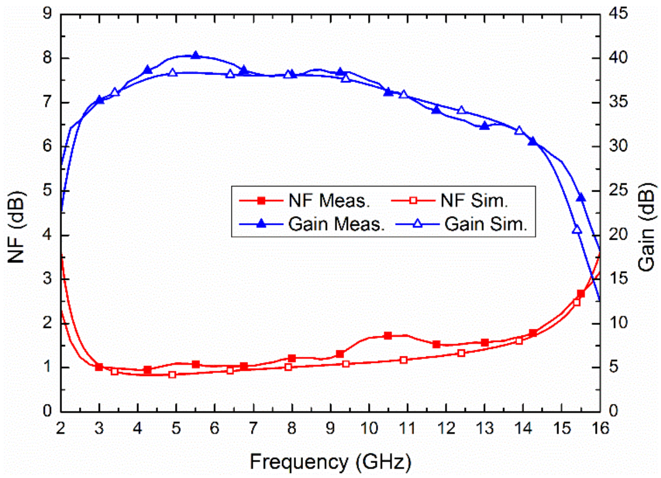

Fig. 10. Measured and simulated results of gain and noise temperature of the amplifier at 300 K room temperature. The bias of the amplifier is supply voltage $V_{CC} = 2$ V and total $I_{CE} = 21$ mA.

The cryogenic cold attenuator technique is the method employed for measuring the gain and noise temperature of the cryogenic amplifier as shown the block diagram in Fig. 11 [30 – 32]. In this technique, two input noise temperatures are applied to the DUT with the hot and cold noise diode temperatures attenuated by the cryogenic input coaxial cable and a cryogenic attenuator. The noise temperatures of the noise diode are obtained from the excess noise ratio (ENR) supplied by the manufacturer with the calibration data. The noise figure analyzer is calibrated connecting the noise source diode to its input. Then, the gain and noise temperature of the whole chain of elements inside the cryostat are measured. In order to determine the DUT noise temperature and gain, the insertion loss of the elements before and after the DUT are de-embedded. Those elements were characterized over the frequency band at the test operating temperature (13 K) in a previous cooling cycle to the DUT measurement. Moreover, an accurate thermal sensor is connected to the attenuator, since its physical temperature is required in order to determine the DUT noise temperature. An external noise source Agilent 346CK01 with a 20 dB attenuator cooled to 13.5 K at the input of the amplifier and the N8975A noise figure analyzer are used to characterize the amplifier.

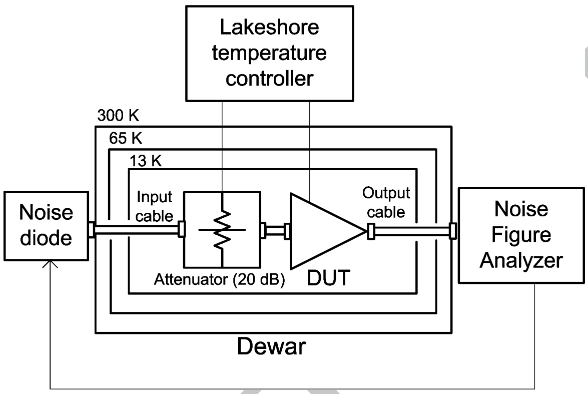

Fig. 11. Block diagram of the cold-attenuator technique for cryogenic gain and noise temperature measurement.

A picture of the Dewar with an inside view of the noise measurement setup is shown in Fig. 12.

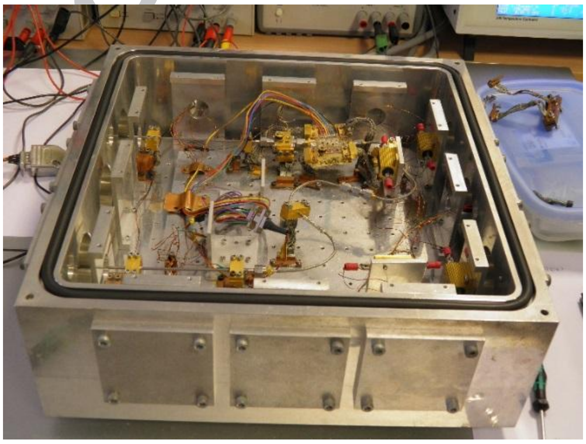

Fig. 12. View of the Dewar with the cold-attenuator measurement setup.

The measured gain and noise temperature of the 3-14 GHz LNA at 13 K are shown in Fig. 13. The amplifier achieves an average gain of 32.4 dB and average noise temperature of 11.4 K over the frequency band, with a minimum noise temperature of 7.2 K at 3.5 GHz. The average gain and noise temperature over the band 4 GHz to 8 GHz is 33.8 dB and 8.9 K respectively. The total power dissipation is 5.8 mW for the optimum low-noise bias. The improvement factor of the noise temperature between 300 K and 13 K ambient temperatures is around 9.

Noise measurements and gain of the amplifier were made at multiple bias levels in the first stage, with fixed bias in the second and third stages at 13 K physical temperature with the aim of evaluating the performance sensitivity to first-stage bias. Fig. 14 shows the average gain and noise temperatures of the LNA from 3 to 14 GHz and from 4 to 8 GHz as function of first stage voltage from 0.6 V to 1.4 V at the collector terminal (V_{CE1}) of the transistor with fixed collector-emitter current of 3 mA. Fig. 15 shows the average gain and noise temperatures of the LNA from 3 to 14 GHz and from 4 to 8 GHz as function of first stage collector current from 1 to 5 mA with fixed voltage V_{CE1} = 0.85 V. For both measurements the second and third stages are biased with 1.0 V and 0.7 V supply voltage respectively and collector-emitter currents of 2.3 mA and 0.95 mA.

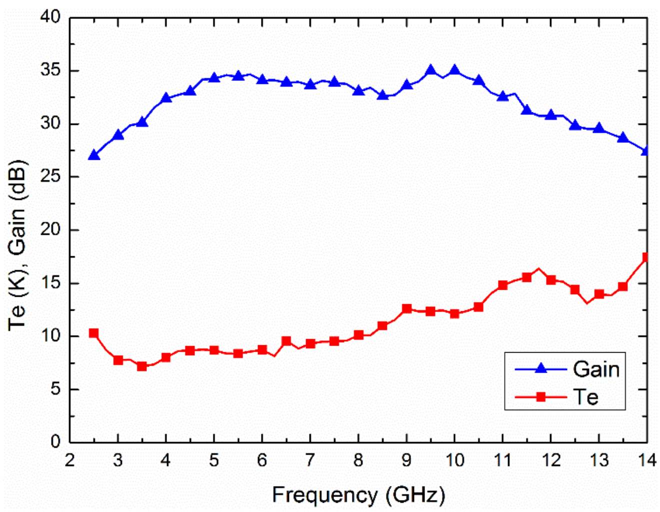

Fig. 13. Gain and noise temperature of the amplifier measured at 13 K ambient temperature. The three transistors of the amplifier are biased with 1.08 V, 0.7 V and 1.0 V supply voltages (V_{CC}), 3 mA, 2.3 mA and 0.95 mA collector-emitter currents.

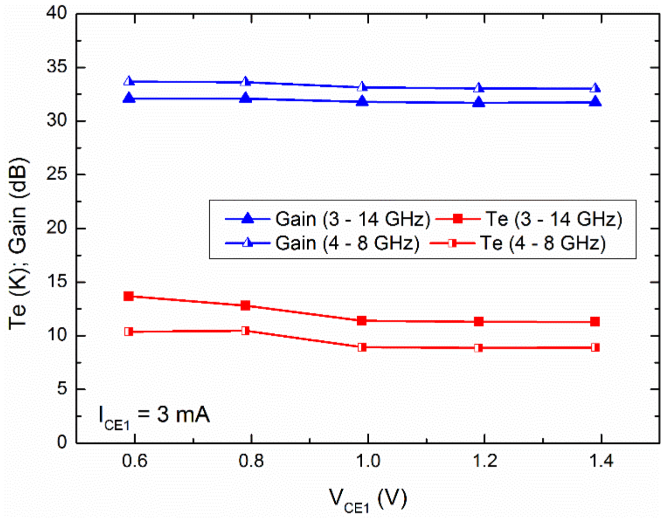

Fig. 14. Measured average gain and noise temperature from 3-14 GHz and 4-8 GHz of the LNA at 13 K ambient temperature versus collector voltage at the collector terminal of the transistor with constant collector current in the first stage I_{CE1} = 3 mA. The second and third stages are biased with 0.7 V and 1.0 V supply voltage respectively and collector-emitter currents of 2.3 mA and 0.95 mA.

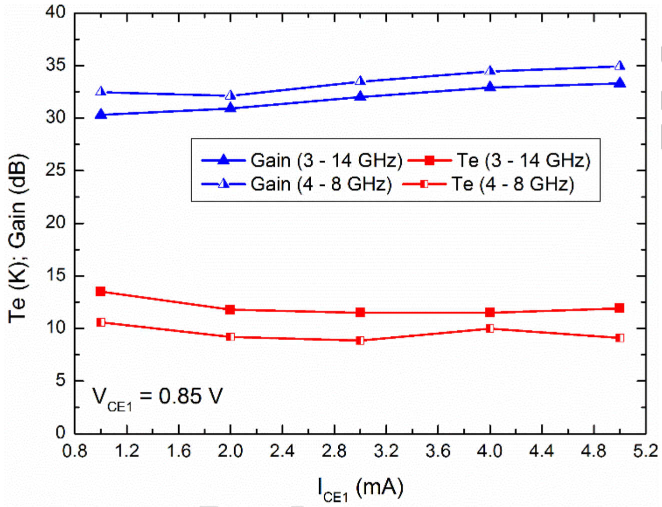

Fig. 15. Measured average gain and noise temperature from 3-14 GHz and 4-8 GHz of the LNA at 13 K ambient temperature versus collector current with constant collector voltage in the first stage V_{CE1} = 0.85 V at the collector terminal of the transistor. The second and third stages are biased with 0.7 V and 1.0 V supply voltage respectively and collector-emitter currents of 2.3 mA and 0.95 mA.

From both measurements, a constant amplifier gain is obtained for a wide range of collector voltages and currents. On the other hand, the noise temperature of the amplifier increases for collector voltages below 0.8 V (see Fig. 14), and a minimum noise is achieved with a constant collector voltage applied (see Fig. 15) for 3 mA of collector current, increasing slightly for lower currents. The cryogenic LNA shows a power consumption of 5.8 mW for optimum noise performance with 13 K physical temperature. The dissipated power of the DUT for the measurements in Fig. 14 varies from 4.36 mW to 6.76 mW, which implies around 1.7 K of change in the DUT physical temperature. The measurements in Fig. 15 are for power dissipations between 3.24 mW and 6.81 mW, which produces a variation of 2.4 K of the DUT physical temperature. These variations of the low-noise amplifier physical temperature do not imply a linear change of its noise temperature, since according to previous works, the noise temperature ceases to decrease at very low physical temperatures below 20 K [33-34].

The measured cryogenic performance of the presented low-noise amplifier is summarized and compared to previously published state-of-the-art cryogenic amplifier results within the same frequency range in Table 1. A figure of merit (*FOM*) which contains bandwidth (*B*), noise temperature (T_e), gain (*G*) and DC power (P_{DC}) has been calculated as:

$$FOM = \frac{G(dB)\cdot B(GHz)}{T_e(K)\cdot P_{DC}(mW)} \tag{4}$$

The presented amplifier has a *FOM* better than most of the state-of-the-art cryogenic amplifiers. Only the best InP HEMT amplifier in [3] presents better FOM because of the low noise temperature, and a SiGe HBT in [12] because of the very low power consumption. Among the SiGe cryogenic amplifier results, this work presents a wider bandwidth with low noise and high gain, being significant the use of low cost packaged transistors.

Table 1. Comparison with other State-of-the-Art Cryogenic Low-Noise Amplifiers.

Ref.	Technology	Freq. (GHz)	Gain (dB)	Noise Temp. (K)	P_{DC} (mW)	*FOM*
[1]	100nm InP HEMT	4-12	37	6	15	4.52
[3]	130nm InP HEMT	0.5-13	38.1	4.4	15	7.2
[4]	InP HEMT	4-12	34	5	9	6.04
[5]	200nm InP HEMT	4-12	27	13	5.7	2.91
[6]	100nm GaAs mHEMT	4-12	31	5.3	8	5.85
[7]	130nm SiGe HBT	8-12	15	21	8.2	2.6
[8]	SiGe HBT	0.5-4	25	9	8.3	1.17
[12]	SiGe HBT	4-8	26	8	0.58	22.4
This work	SiGe NPN	3-14	32.4	11.4	5.8	5.39
This work	SiGe NPN	4-8	33.4	8.9	5.8	2.58

5. Conclusions

The performance of bipolar SiGe transistors at cryogenic temperature has been analysed through the design, fabrication and characterization of a 3 – 14 GHz cryogenic low-noise amplifier. The three stage amplifier designed uses plastic packaged transistors model BFU910 from NXP. The use of these transistors has demonstrated neither mechanical failure of the packaged devices when thermally cycled between cryogenic and ambient temperatures due to mismatched thermal-expansion coefficients, nor electrical malfunction. Moreover, the amplifier exhibits a gain of 32.4 dB and an average noise temperature of 11.4 K in the 3 to 14 GHz frequency band, with 5.8 mW of power consumption at an ambient temperature of 13 K. Therefore, this low-noise amplifier demonstrates an excellent cryogenic performance with a low power consumption using low-cost commercial Si-based technology transistors. As a result, the low cryogenic noise temperature and power consumption values of the amplifier make the used transistor well suited for very low-noise cryogenic amplifiers needed in radio astronomy, space communications or high sensitivity systems for physics research.

Acknowledgements

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