30GHz SiGe Monolithic LNA

J. Costa Freire[1], Reza Mahmoudi[2] and Arthur van Roermund[2]
[1]Instituto de Telecomunicações, Instituto Superior Técnico
Av. Rovisco Pais, 1049-001 Lisboa, Portugal
Phone: +351 21 8418483 Fax: +351 21 8418472
E-mail: jcf@lx.it.pt
[2]Technische Universiteit Eindhoven, Faculteit Elektrotechniek, MsM group
Postbus 513, 5600 MB Eindhoven, Nederland
Phone: +31 40 2473642 Fax: +31 40 2455674
E-mail: r.mahmoudi@tue.nl

Abstract — **In this paper a study of the performance of SiGe QUBiC4G technology to be used on 30GHz LNAs is presented. The best HBT for this purpose is selected. For this HBT and I_C bias current leading to NF_{min}, simple LNAs were designed: common emitter with resistive and inductive bias; and cascode. The results show the possibility of using the QUBiC4G technology, optimised for low microwave applications (few GHz), at the low millimeter wave band - NF≈5dB, G≈5dB per HBT.**

Key words — **SiGe MMIC; Millimeter wave; Low noise amplifier; SiGe HBT.**

I. INTRODUCTION

The increase of the SiGe technology performance on the last decade has been pushed mainly by the consumers' telecommunications market and the expected price advantage of nearly one order of magnitude over the GaAs technologies is fore seen [1]. Presently SiGe HBTs are competing with HFET and PMFET on monolithic low noise applications with a much lower cost at microwave frequencies (up to 5-6GHz) and start to challenge them at the lower millimeter wave band (≈30GHz). At lower millimeter wave band, devices with NF=1.5dB @ 26GHz [2] and LNAs with NF≈4dB @ 23GHz [3] and receivers RF front end @ 24GHz with NF=7dB [4] and NF=9dB [5] were reported recently.

In this paper is presented the results on the study of QUBiC4G Monolithic Technology [6] performance at 30GHz to implement LNAs. This technology was optimised for a frequency range one decade lower but results on 20GHz were already published [7].

The design of bipolar monolithic LNAs starts with the choice of the best transistor dimensions (emitter length L_e and width W_e) and collector current density J_C. For this purpose, based on Cadence simulation, we have obtained for 30GHz the minimum NF_{min} and maximum gain G_{max} (MAG when unconditionally stable and MSG when conditionally stable) as a function of J_C for transistors with the minimum emitter length (0.5µm) using the device more suited for low noise applications, the NPN HBT BNA [6].

For the best HBT and I_C bias current leading to NF_{min}, simple LNAs were designed. For high frequency bipolar transistors LNAs, several topologies have been used in the past. The simpler common emitter (CE) that presents the advantage of high power gain, the single common base (CB) used due to its low reverse gain and high cut off frequency, however has a lower power gain, and the cascode (CC=CE+CB) since it has high cut off frequency, due to the reduced Miller effect on the first stage (CE), low reverse gain due to the CB and power gain similar to the CE. For an input simultaneously noise and conjugate matching we have used the series feedback inductor on the common emitter stage. This inductor increases the input resistance of the amplifier. On the cascode, for the same reason, an inductor was used in series with the emitter of the first stage (CE).

The simulation predicts G_{max}=4.6dB and NF_{min}=3.5dB for a common emitter with a collector resistive bias. With a spiral inductor on the collector bias (lower power consumption but higher silicon area) the CE presents G_{max}=3.3dB and NF_{min}=4.6dB. For a cascode we have obtained very similar values but the 1dB compression point P_{1dB}, is lower (V_{CE} lower in each HBT).

II. CHOICE OF HBT DIMENSIONS AND BIAS

According to the Design Manual of QUBiC4G, the BNA transistor is recommended when low base resistance is needed. This resistance thermal noise is one of the key elements on the HBT noise figure calculation. Another is the collector current, due to the Schottky noise, generated on the junctions. Since the base resistance increase with the emitter width W_e, and decrease with the emitter length L_e, the choice of the best HBT was mainly based on those with minimum emitter width.

The study of the BNA HBTs performance for LNAs at 30GHz was based on Spectre simulations using foundry models [6]. In figure 1 to 4 is presented the minimum noise figure NF_{min}, and maximum gain G_{max}, for four transistors with minimum base width (W_e=0.5µm) and emitter length L_e=1µm, 4.7µm, 10.3µm and 20.7µm, all foundry library preset L_e values. For each HBT, several values of collector current I_C were simulated. In order to introduce on this study the bias network effect, a simple base bias resistance between collector and base was used (DC parallel feedback). The collector-base voltage V_{CB}, is close to 1V, the value for which f_T (unity current gain frequency) is specified on the Design Manual [6]. The collector DC bias source (V_{CC}) was adjusted accordingly.

The longer HBT, Fig.1, L_e=20.7µm, presents the higher maximum gain (G_{max}=10.7dB) with a slightly higher NF_{min} (3.4dB). This device also presents an R_n close to 50Ω (≈30-70Ω), predicting a simple input matching network, which is important to avoid losses and related NF degradation. However, a high bias current (I_C≈2mA) is needed for NF_{min} or G_{max}.

From Fig. 4 it is noticed that the smallest device (0.5µmx1.0µm) presents the lowest NF_{min} (2.85dB) but the maximum gain G_{max} (3.85dB) is very low. The equivalent noise resistance R_n is very high (≈400-500Ω), predicting a difficult minimum noise matching.

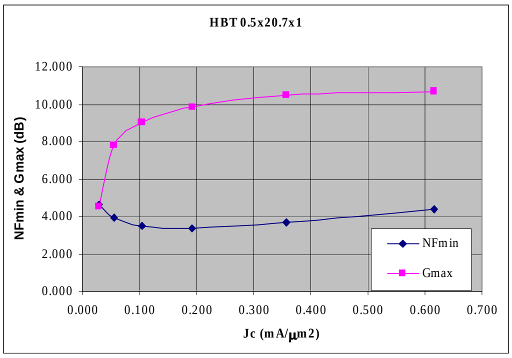

Fig 1. – 30GHz NF_{min} and G_{max} vs J_C for HBT 0.5µmx20.7µm

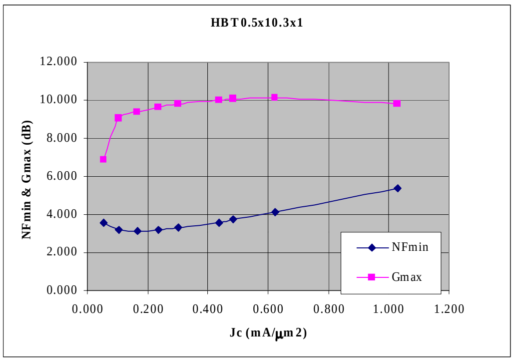

Fig 2. – 30GHz NF_{min} and G_{max} vs J_C for HBT 0.5µmx10.3µm

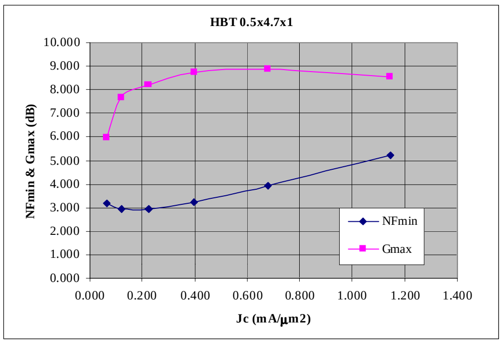

Fig 3. – 30GHz NF_{min} and G_{max} vs J_C for HBT 0.5µmx4.7µm

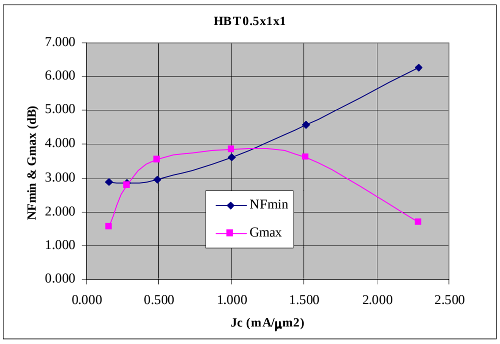

Fig 4. – 30GHz NF_{min} and G_{max} vs J_C for HBT 0.5µmx1.0µm

Accordingly, this device presents a good compromise when high gain and minimum noise is needed, without power consumptions constraints.

Taking into account, the bias current, a better compromise is obtained with the 0.5µmx4.7µm, Fig. 3 (NF_{min}=2.9dB @ I_C≈0.5mA with G_{max}=8.2dB and R_n≈120Ω).

Two HBTs with wider emitter (W_e>0.5µm) were tested with emitter area similar to the 0.5µmx10.3µm (0.8µmx6.3µm and 1.5µmx3.1µm). Both present higher NF_{min} and lower G_{max}, confirming the theoretical predictions.

From Fig. 1 to 4 we noticed that NF_{min} presents a minimum for a given current density (J_C≈0.2mA/µm^2). The best device was the 0.5µmx20.7µm since it presents an NF_{min}≈$NF_{50\Omega}$, avoiding the use of input matching network with passive components with low Q and parasitic effects that degrades directly the noise performance.

Accordingly, for further studies the following transistor was chosen:

HBT 0.5µmx20.7µm with I_C≈2mA (J_C=0.19mA/µm^2)

III. COMMON EMITTER LNA

The simpler topology used on HBT LNAs is the common emitter (CE) that presents the advantage of high power gain.

The HBT 0.5µmx20.7µm with $I_C \approx 2$mA, for a 50Ω input drive source presents a NF=3.7dB close to the NF_{min}=3.4dB. The device is unconditionally stable at 30GHz (K=1.11) accordingly, a simple common emitter amplifier with an input direct coupled high capacitor (C_I>2pF) was tested. The circuit was designed for 28.5GHz, the center frequency of LMDS system [8]. For the output a LC matching network was designed for maximum gain. The simple amplifier circuit is presented in Fig. 5.

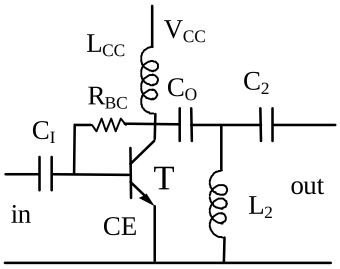

Fig. 5 – Common emitter LNA

The bias resistance R_{BC}=125K and the choke inductor L_{CC}, should be greater then 2nH. The output matching network has a parallel inductor L_2=0.425nH and a series capacitor C_2=57.4fF. The circuit has a transducer power gain G_T=7.4dB and NF=3.7dB. The input return loss is only 4.7dB. To obtain better input return losses with low NF, the usual series feedback inductor was introduced [9]. With an 80pH feedback inductor, L_2=0.480nH and C_2=52.6fF a NF=3.4dB (NF_{min}=3.3dB) and a G_T=6.6dB (G_{max}=7.2dB) is obtained. The input return losses (without any matching network) is 9.5dB and the output is ideally matched (<-60dB) with a 10dB return loss bandwidth of almost 10GHz (wide band).

To simulate the circuit with real components, since L_e is very small to be obtained with only one turn (4 sections), we have increased its value to 100pH and introduced in series a resistance of 1.25Ω to simulate a Q=15 @ 30GHz [7]. For bias resistor R_{BC} a poly N-resistor RPZ was used, with the lower allowed width 0.5µm, due to its higher R and low parasitic [6]. For L_2 output inductor we have used a 550nH @ 30GHz spiral inductor [7], and adjusting the matching with C_2. The main problem, to implement Fig. 5 circuit with QUBiC4G technology is the availability of a bias chock inductor. Since it is not available inductors with L>2nH and a series resonant frequency SRF>30GHz we have tried to use the QUBiC4G 1nH (5x33x300) inductor, but G_{max} drop to 2.1dB and NF_{min} increases to 4dB. An alternative solution using L_{CC} also as matching inductor and already with the series emitter inductor L_e is presented in Fig 6. With 100pH+1.25Ω feedback inductor L_e, L_{CC}=550nH @ 30GHz, C_I=1pF and C_2=100fF, both QUBiC4G MIM capacitors, a NF=3.9dB (NF_{min}=3.6dB) and a G_T=3.3dB (G_{max}=4.1dB) with $|s_{11}|$=-8.8dB and $|s_{22}|$=-13.6dB was obtained at 28.5GHz.

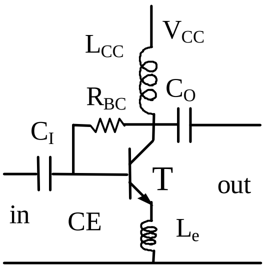

Fig. 6 – Common emitter LNA with L_e series feedback and L_{cc} as bias and matching inductor

Due to the reduced gain, further investigations based on the Fig.5 solution were carried out. The chock inductor L_{CC} was substitute by a resistor R_{CC} and V_{CC} was increased to the maximum safe operating value 2.7V (10% higher then typical value). For this resistor implementation a RPN, poly N+, was used, since it is the one presenting better RF performance [6]. With R_{CC}=750Ω, V_{CC}=2.7V, R_{BC}=25kΩ (I_C=2.15mA), 100pH+1.25Ω feedback inductor L_e, L_2=550nH @ 30GHz, C_I=C_O=1pF and C_2=0fF, since its value is very low (10fF), a NF=3.7dB (NF_{min}=3.4dB) and a G_T=3.9dB (G_{max}=4.4dB) with $|s_{11}|$=-11.9dB and $|s_{22}|$=-18.8dB was obtained at 28.5GHz, after several adjustments.

IV. CASCODE LNA

The more commonly used topology for LNAs is the cascode (CC), common emitter cascaded with a common base, because on a first analysis it must have: an high cut off frequency, due to the reduced miller effect on the first stage; lower reverse gain, due to the common base lower internal feedback, accordingly, more stable; and high gain, similar or greater then the simple common emitter. However, our simulation results present some instability problems and the gain is only higher when the devices are conditionally stable. Following the results of such studies are presented.

A simple one stage cascode was studied (Fig.7). The same device was used on both HBTs for the reason above referred about the CE (lowest $NF_{50\Omega}$). For simultaneously noise and conjugate matching at the input a series feedback inductor L_e on the emitter of the first transistor was used [9]. The bias inductor L_{CC} is also used as matching inductor. With ideal components the circuit is conditionally stable up to a frequency higher then 30GHz. However, when QUBiC4G library components are introduced, the circuit is unconditionally stable from 1 to 60GHz.

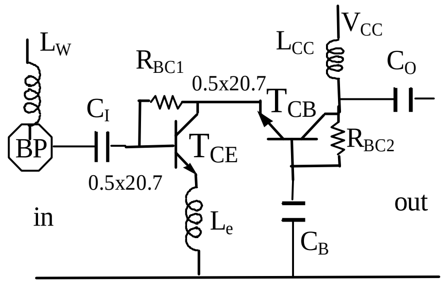

Fig.7 - Cascode LNA with inductor bias

The simulation results including a bond pad (BP) and wire bond (L_W) are presented on Fig.8 to 10.

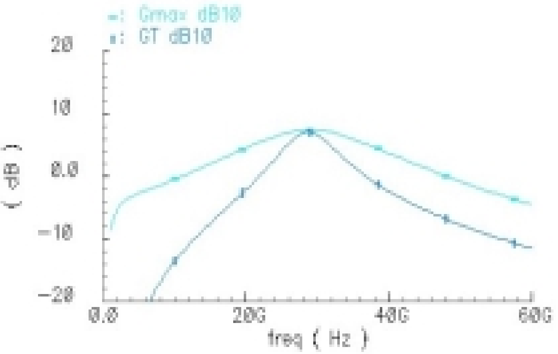

Fig. 8 - Cascode with inductor collector bias results
Power Gain in dB (transducer and maximum)

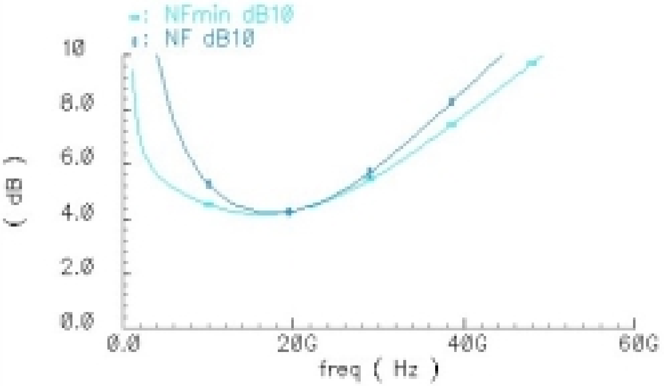

Fig. 9 - Cascode with inductor collector bias results
Noise Figure in dB (50Ω and minimum)

The components values are given on Table 1.

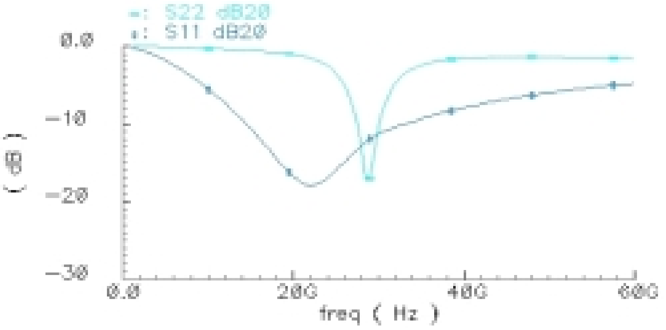

Fig. 8 - Cascode with inductor collector bias results
Return Losses in dB (output and input)

Table 1 - Fig.7 components values

name	L_W	BP	$R_{BC1,2}$	L_e	C_I	C_O	L_{CC}
type	wb	octg	PZ	ideal	MIM	PDN	[5]
value	240	-	45	150	1	35	440
unity	pH	-	kΩ	pH	pF	fF	pH
physic. dim.	2//x0.5	65	0.5x10	Q=15	14x14	3x2	-
unity	µm	µm	µm	-	µm	µm	-

A NF=5.6dB (NF_{min}=5.4dB) and a G_T=7dB (G_{max}=7.4dB) with $|s_{11}|$=-12.3dB and $|s_{22}|$=-17dB was obtained at 28.5GHz. The gain is better then with the common emitter but the NF is higher.

V CONCLUSIONS

It was shown that is possible to use QUBiC4G technology to design LNAs at the low edge of millimeter wave band (30GHz). The best transistor for this application is the SiGe HBT type BNA with an emitter with 0.5µm width and 20.7µm length. The collector current density, for minimum noise figure, for all transistors tested is J_C=0.19mA/µm^2. Accordingly, the 0.5µmx20.7µm HBT should be biased with I_C≈2mA.

Simple common emitter stages with technology lumped elements (bias poly resistors, MIM capacitors and spiral inductors) were designed. The best solution uses a collector bias resistor and presents a gain G_T=3.9dB with a noise figure NF=3.7dB.

To increase the gain a cascode amplifier was designed. With a collector bias/matching spiral inductor it presents a gain G_T=7dB and a noise figure NF=5.6dB.

The common emitter have a lower NF, however, if we increase the gain cascading two similar stages, the gain increases to 8dB but the NF increases to 5.5dB. This solution has the drawback of having more spiral inductors then the cascode (3 instead of 2) and this lumped element is the one with larger Si area.

REFERENCES

[1] Peter Nuecher, “Silicon based Monolithic Integrated Microwave Systems – Present Limitations and Future Aspects”, Si Monolithic ICs in RF Systems Conference, pp19-22, 2000.

[2] D. R. Greenberg et. al., “Noise Performance of a Low Noise Base Resistance 200GHz SiGe Technology”, International Electron Devices Meting, pp787-790, 2002.

[3] Yinggang Li et. al., “23 GHz Front-end Circuits in SiGe BiCMOS Technology”, Radio Frequency Integrated Circuits Symposium, pp99-104, 2003.

[4] Ian Gresham et. al., “Ultra Wide Band 24GHz Automotive Radar Front-End”, Radio Frequency Integrated Circuits Symposium, pp505-508, 2003.

[5] E. Sonmez et. al., “A single-chip 24GHz Receiver Front-end Using Commercially Available SiGe HBT Foundry Process”, Radio Frequency Integrated Circuits Symposium, pp159-162, 2003.

[6] “QUBiC4/4G Library Manual”, Philips Semiconductor, 2002.

[7] P. Deixler et. al., “QUBiC4G: A fT/fmax=70/100GHz 0.25µm Low Power SiGe-BiCMOS Production Technology with High Quality Passives for 12.5Gb/s Optical Networking and Emerging Wireless Applications up to 20GHz”, Bipolar/BiCMOS Circuits and Technology Meeting, 2002.

[8] LMDS standard IEEE 802, provisional documents.

[9] R. E. Lehmann and D. D. Heston, “X-band monolithic series feedback LNA”, IEEE Trans. on Electron Devices, vol. ED-32, pp2729-2735, December, 1985.