SiGe MMICs with Spiral Inductors up to millimetre waves

Jorge Alves Torres† and J. Costa Freire*

†*Instituto de Telecomunicações, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal

Phone: +351-218418483, Fax: +351-218418472, e-mail: jtorres@lx.it.pt

†Instituto Militar dos Pupilos do Exército; *Instituto Superior Técnico, Technical University of Lisbon

Abstract — **The performance up to millimetre wave of a 0.25µm BiCMOS SiGe technology optimized for applications up to 10GHz is presented. Since the library available spiral inductors has series resonant frequency (SRF) lower than 30GHz, spiral inductors with higher SRF were designed, implemented and tested. For those inductors, lumped circuit equivalent models were derived and the models were used to design two illustrative MMICs, a low noise amplifiers and a VCO. Both MMICs were fabricated and tested. The results show the possibility of using this technology with spiral inductors up to millimetre wave band lower edge with good results.**

I. INTRODUCTION

Presently, the monolithic silicon based technologies are already competing in the low microwave band applications (few GHz) with advantages [1], and they start to compete with the III-Vs technologies at higher frequencies, achieving the millimetre waves, mainly due to the SiGe BiCMOS technologies and the high f_T and f_{max} achieved by their HBTs [2-4]. Their drawbacks are the lower performance of the passive elements, specially the inductors [5].

In the past the authors have showed the possibility of using a 0.25µm SicGe BiCMOS technology without inductors up to 30GHz [6]. The used low cost technology (SG25H3 [7]) is optimized for applications up to 10GHz. The smallest available spiral inductors have a series resonant frequency (SRF) close to 30GHz. Accordingly, the design, implementation and test of spiral inductors with higher SRF are presented on section II.

The design and implementation of key active circuits using those inductors is discussed. In Section III an LNA and in Section IV a VCO are presented.

Finally, the conclusions and future work are discussed on Section V.

II. SPIRAL INDUCTORS WITH HIGH SRF

Since the objective of this study is to use spiral inductors at millimetre waves, several smaller inductors were designed, fabricated and tested to achieve SRF higher than 30GHz. The ones with higher SRF have one and two turns with metal strips width of W=10µm, using three overlapped metal levels (M2, M3 and M4). The spacing between turns and input strips is S=5µm. The internal sides are 25µm apart. Guard-rings connected to substrate and ground pads were used (figure 1).

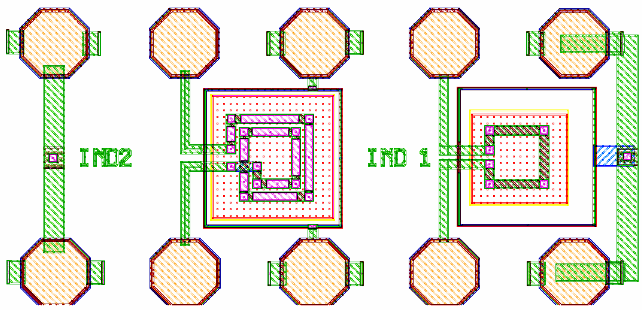

Fig. 1. One (IND1) and two (IND2) turns spiral inductors layout

A lumped model for the spiral inductors core was obtained (Fig. 2) fitting the simulations with inductor measured s parameters, following a step by step process converting the s-parameters on y or z-parameters to extract the model elements values in parallel or series, respectively [8]. To obtain the inductor core measured s parameters the pads and connection lines were de-embedded. In both inductors the input and output connection lines were similar. Accordingly, the same values for the RL series at the input and output ports (R_{Lin}=R_{Lout}=0.45Ω and L_{Lin}=L_{Lout}=90pH). The pads effects were modelled by a capacitor C_{pad}=29.2fF in series with a parallel RC of $C_{pad\ par}$=8.4fF and R_{pad}=238Ω.

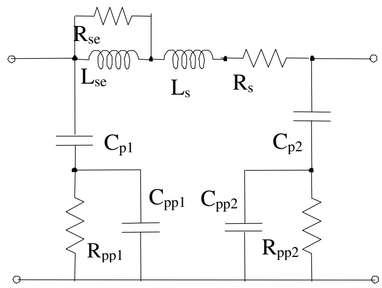

Fig. 2. Spiral Inductor core RLC lumped model

In Fig. 3 and 4 is presented the comparison between measured and simulated s-parameters using Fig. 2 model for one turn and two turn inductors. It can be noticed that both inductors have SRF greater than 45GHz. At 30GHz the smaller inductor has an equivalent inductance of 135pH and the larger 330pH. Both values are smaller than the inductance of the smallest available simple inductor on the foundry library (1nH), and with a much higher series resonance frequency.

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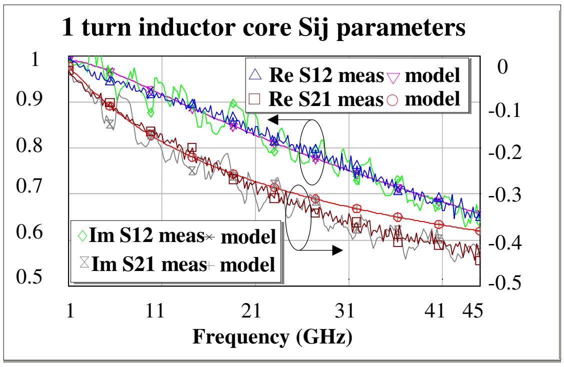

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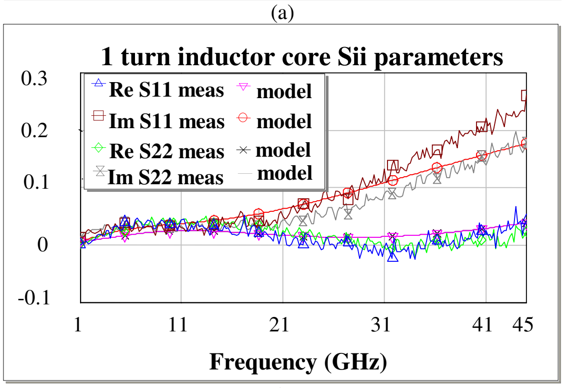
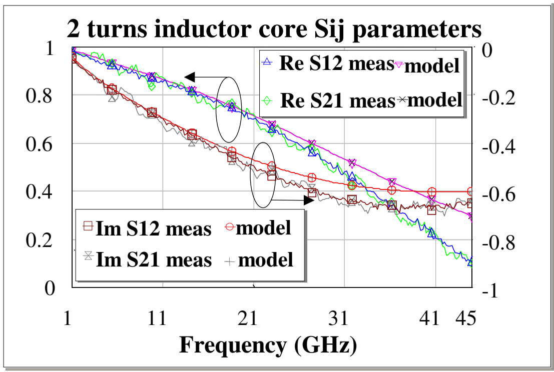


(b)

Fig. 3. One turn inductor core of Fig. 1 measured and simulated s-parameters with the derived lumped model of Fig. 2: L_{se}=0.1nH, R_{se}=7.1Ω, L_s=125.8pH, R_s=0.7Ω, C_{p1}=C_{p2}=25fF, C_{pp1}=C_{pp2}=1fF, R_{pp1}=R_{pp2}=177.5Ω.



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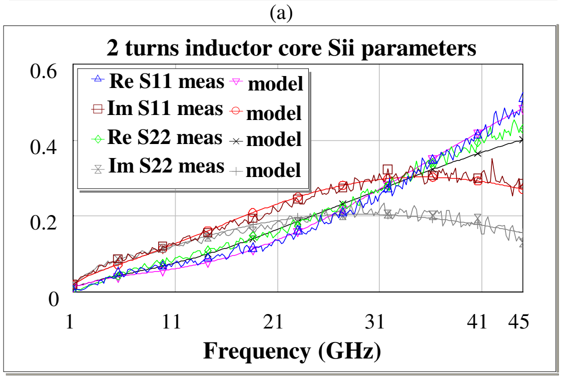

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Fig. 4. Two turns inductor core of Fig. 1 measured and simulated s-parameters with the derived lumped model of Fig 2: L_{se}=0.166nH, R_{se}=4.68Ω, L_s=327.8pH, R_s=1.19Ω, C_{p1}=C_{p2}=32.9fF, C_{pp1}=26.6fF, C_{pp2}=18.6fF, R_{pp1}=315Ω, R_{pp2}=91.2Ω.

III. LOW NOISE AMPLIFIER

In Fig. 5 a cascode amplifier with reactive series feedback, for having a good compromise noise matching, is introduced using the spiral inductors presented in section II.

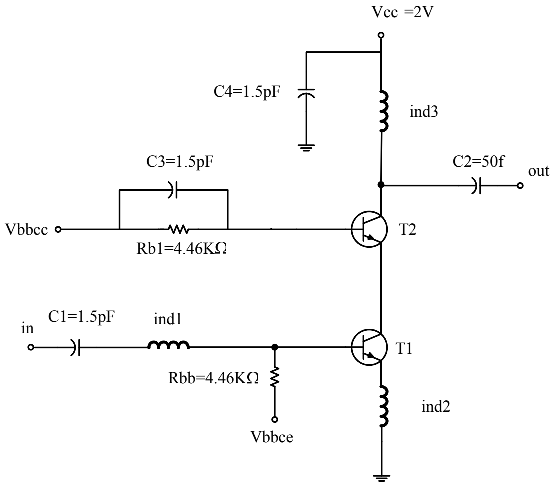


Fig. 5. Cascode LNA with series reactive feedback.

Spiral inductors were also used for input and output matching to compensate the HBTs capacitive effects. The LNA was optimized for Matching, Noise and Gain at 28.5GHz and the best solution was obtained with the input and output inductors (ind1 and ind3) with two turns and the feedback inductor (ind2) with 1 turn. At 28.5GHz the predicted gain is 8dB, noise figure is 5.5dB, the input return losses are better than 20dB and output return losses are better than 11dB. The fabricated prototype layout is presented in Fig. 6.

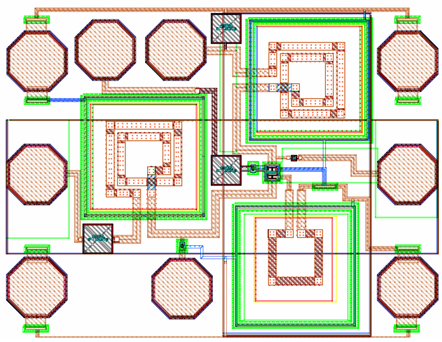


Fig. 6. Cascode LNA layout.

The Silicon area is 580µm×440µm=0.255mm^2. The DC bias voltages for the above mentioned performance are: Vbbce=0.9V (Ibbce=9.6µA), Vbbcc=1.8V (Ibbcc=9.62µA), and Vcc=2V (I_C=1.67mA), leading to V_{CE2}=1.1V; V_{CE1}=0.9V. The current gain β is 172 and I_B is about 9µA for both HBTs.

The LNA was fabricated and tested on-wafer. The comparison between experiments and simulations are presented in Fig. 7 to 10.

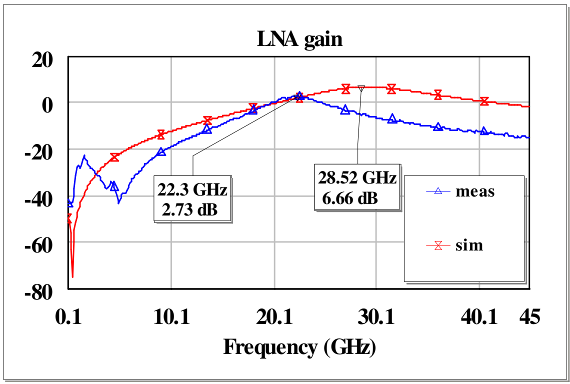


Fig. 7. Simulated and measured Cascode LNA gain

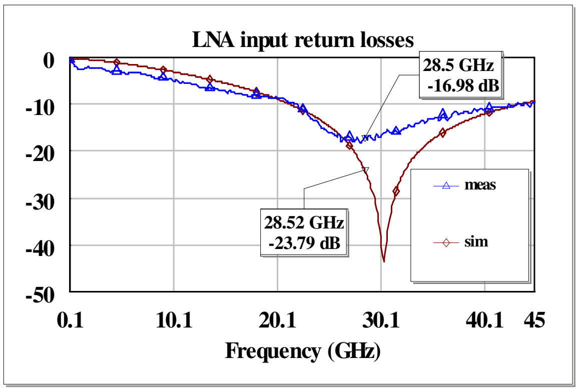


Fig. 8. Simulated (two bias conditions) and measured Cascode LNA input return losses.

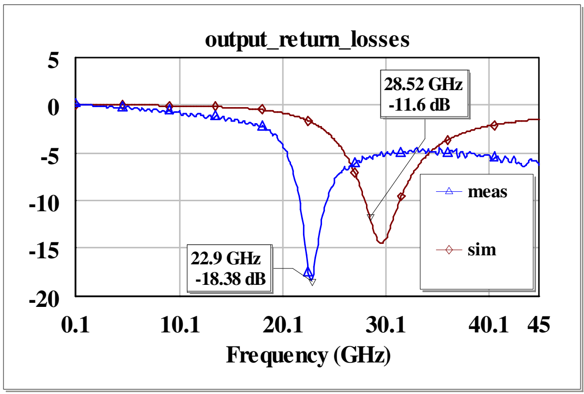


Fig. 9. Simulated (two bias conditions) and measured Cascode LNA output return losses.

The worth result was obtained for the gain. It is partially due to a bad RF ground at T2 base. All the other results are closer to the predicted ones with a shift in frequency. The simulation with a RL series of R=100Ω and L=2nH, in series with Vbbcc and adding 120pH to the 2 turn's inductors, the predicted inductance of its connection lines [8], leads to the gain reduction and frequency shift observed experimentally. A new version of the LNA with an on-wafer RF bypass capacitor and redesigned input and output networks with the inductors access lines is under fabrication.

In the past was implemented by the authors two inductor less LNAs. The matching and NF were very similar however the simulated gain was higher [6]. Accordingly, the spiral inductors should only be used when no other solution is presented.

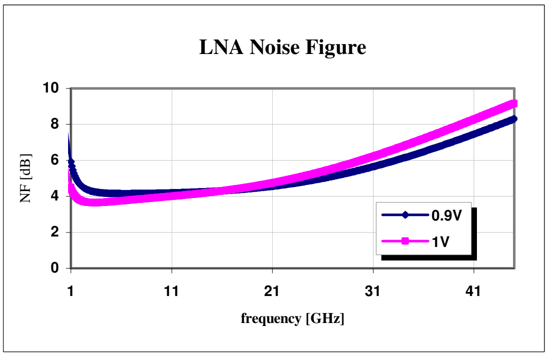
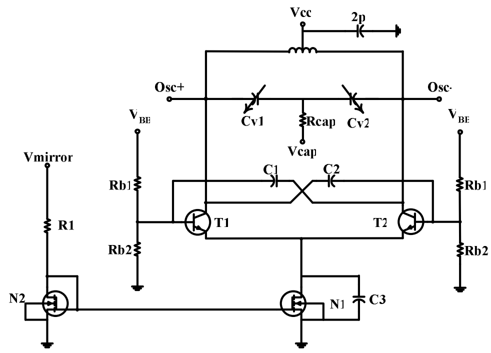


Fig. 10. Simulated (two bias conditions for V_{bbce}) Cascode LNA NF: V_{bbce}=0.90V, V_{bbcc}=1.8V, I_{cc}=1.65mA and V_{bbce}=1.0V, V_{bbcc}=1.8V, I_{cc}=3.79mA.



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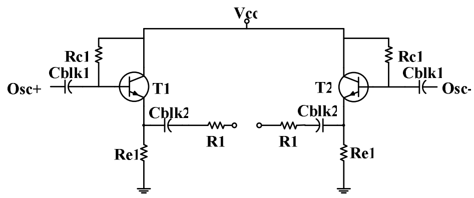

(b)

Fig. 11. VCO circuit schematic: (a) core and (b) buffer.

IV. LC VOLTAGE CONTROL OSCILLATOR

One of the most important specifications of VCOs is the phase noise that is dependent on the resonator Q factor. Following, an important element on the performance of Fig. 11 VCO is the resonator's tapped-inductor (Fig. 11a – VCO core) due to its relatively low Q. We have used the foundry library smallest available spiral inductor which has two turns. This inductor is also the only one with a series resonant frequency higher then 30GHz. Its foundry model is only reasonable accurate up to 10GHz, probably because this technology was optimized to be used in applications on this frequency range. Accordingly, to design the VCO, an accurate model up to 40GHz was developed by the authors [9].

The VCO was optimized to operate on a frequency range around 15GHz to be used on a 30GHz receiver as Local

Oscillator on a harmonic mixer. The varicaps are NMOSTs with 4×1µm×10µm (4 fingers). When the varicap control voltage is changing from 0 to 2V the VCO frequency is changing from 13.1GHz to 17GHz.

The VCO buffer (Fig. 11b) is a dual common collector amplifier DC decoupled from the VCO core circuit (Fig. 11a). The buffer is decoupled from the core through a capacitor of 400fF.

In Fig. 12 is presented the final layout of the VCO. More than 50% of the active area is the spiral tapped-inductor.

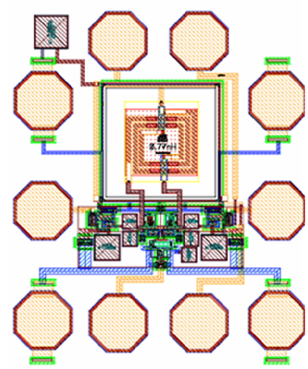

Fig. 12. VCO with buffer layout

The pads, starting from the lower right corner opposite counter clock, are: ground, output signal, ground, V_{BB} (2V-0.48mA), V_{CC} (2V-16.3mA), ground, output signal, ground, V_{mirror} (1.3V-550µA) and V_{cap} (0V to 2V).

The prototype was tested on wafer. For V_{mirror}=1.1V (I_{mirror}=0.40mA), V_{BB}=2V (I_{BB}=0.60mA) and V_{CC}=2.4V (I_{CC}=16.7mA), which are close to the simulation conditions, we have obtained the results presented in figure 13 and 14. Fig. 13 presents the oscillator frequency f_{osc} versus varicap control voltage V_{cap}. The measured values are 1GHz lower than the simulations (-7%), however the frequency range is the same (Δf_{osc}=4GHz). This frequency shift is smaller than the verified on the LNA but of the same sign showing that the foundry models accuracy at 30GHz is worth than at 15GHz.

Fig. 14 presents the output spectrum for a control voltage of 2V (f_{osc}≈16GHz). The measured output power is closed to the predicted value (-10dBm).

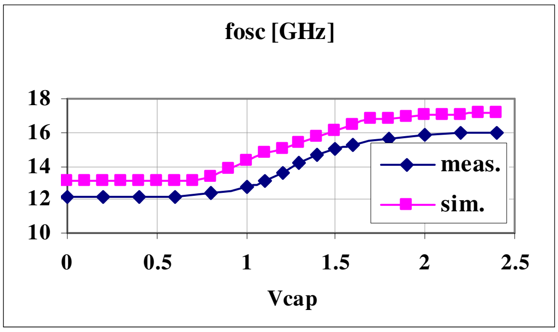

Fig. 13. VCO oscillation frequency versus control voltage

V. CONCLUSIONS

Spiral inductors with SRF higher than 45GHz, not available at the foundry library, were designed, tested and used on a cascode LNA for a 28.5GHZ receiver. The only foundry library spiral inductor with a SRF higher than 30GHz, a taped inductor, was used on a 15GHz VCO. The results of both MMICs show the possibility of using the low cost 0.25µm Si Ge technology on components for 30GHz receivers with spiral inductors. A new version of the LNA is under fabrication. The performance of other components, such as mixers is also being studied.

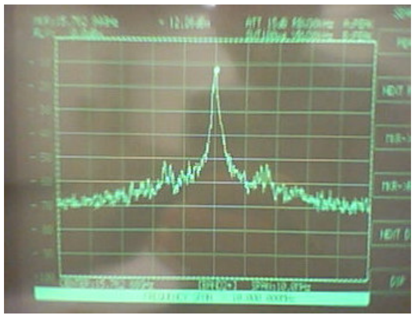

Fig. 14 VCO output spectrum.

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