A 3 to 5 GHz UWB SiGe HBT Low Noise Amplifier

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***Abstract*—Ultra-wideband low-noise amplifiers (UWB LNA) operating in the low-frequency band (3.1–5 GHz) of UWB spectrum are presented. The designs consist of a cascode amplifier with wideband input matching techniques based on LC-ladder filters or shunt-feedback both combined with inductive peaking. Implemented with a SiGe HBT process, the LNAs give 18.0 dB gain, better than -20 dB input matching, and a return loss less than -34 dB, while consuming 11 mW under 1.5 V supply. The feedback LNA gives a better flat noise figure of 2.5 dB and an input IP3 of -6 dB at 5 GHz.**

***Index Terms*— LNA, UWB, wideband matching, shunt-feedback Introduction**

I. INTRODUCTION

Although the ultra-wideband (UWB) standard (IEEE 802.15.3a [1], [2] has not been completely defined, there has been an increasing interest in the low-frequency band (3.1-5 GHz) of the UWB allocated frequency range (3.1-10.6 GHz). A major proposal proposes that data rates of up to 400-480 Mb/s can be obtained using the low-frequency band alone. This frequency band has been allocated for the development of the first-generation UWB systems (>100 Mb/s) targeting low-power wireless multimedia applications and high-performance PC peripherals over a short distance up to 10 m. So far, wideband designs are dominated by three different topologies: the distributed amplifiers, resistive shunt-feedback, and recently the LC-ladder filter matching. Two major drawbacks of the distributed amplifiers is that they tend to consume large dc power due to the distributed multiple stages and are not optimized for low noise [3], [4]. The resistive shunt-feedback broadens the working frequency in terms of input impedance matching, gain, and linearity [5], [6]. Also, it reduces the circuit sensitivity to external factors such as biasing, process tolerances, and temperature. However, in narrow-band systems the feedback resistance must be small to match 50 Ω, hence degrading the noise figure. The LC-ladder match gives good wideband performance with low dc power [8], [9]. However, the reactive elements used in such systems tend to occupy large chip area and degrade the noise figure in case of on-chip implementation.

This paper presents low-noise, low-power, and good linearity SiGe BiCMOS HBT amplifiers and compares the performance characteristics of the shunt-feedback and LC-ladder filter matching techniques in the UWB 3.1-5 GHz band. The HBT device was chosen because of its higher maximum available gain (MAG) and the ease to obtain an unconditional stability over a wide bandwidth owing to its lower impedance.

II. DESIGN USING LC-LADDER FILTER MATCHING

The proposed topology, shown in Fig. 1, uses a cascode amplifier embedded in a bandpass LC filter for input matching over the passband.

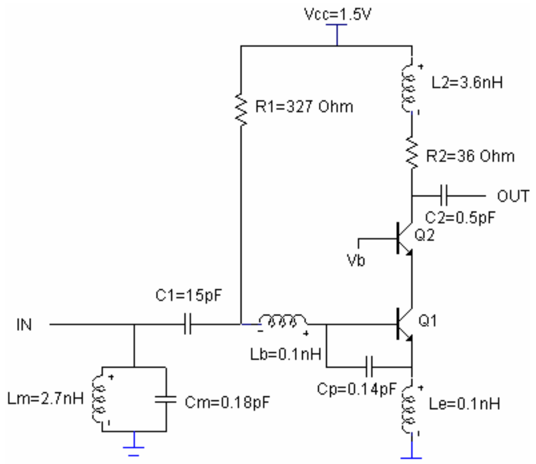

Fig. 1. schematic of a wideband amplifier using LC-Ladder filter matching.

Here, the matching circuit elements are chosen so that [8]

$$L_m \approx \frac{R_S}{w_L} \quad \text{and} \quad L_e \approx \frac{R_S}{w_U} \tag{1}$$

$$C_m \approx \frac{1}{w_U R_S} \quad \text{and} \quad C_t \approx \frac{1}{w_L R_S} \tag{2}$$

where w_L and w_U are the lower and upper frequencies of the input bandpass filter, which embeds the total capacitance $C_t = C_\pi + C_p$ between base and emitter, the emitter-degenerating inductance L_e and the resistance $w_T L_e$ is the designed to equal the source resistance R_S (50Ω) over the entire bandwidth of resonance w_U-w_L.

The voltage gain of the amplifier was derived as

$$\frac{v_{out}}{v_{in}} = \frac{-g_{m1}}{sC_t}\frac{W(s)}{R_S}Z_{cd}(s)\frac{R_2\left(1+s\frac{L_2}{R_2}\right)}{1+sR_2C_{out}+s^2L_2C_{out}} \quad (3)$$

where g_{m1} is the transconductance of Q_1, $W(s)$ the transfer function of the bandpass filter equals R_S over the bandpass, C_{out} the total capacitance at the collector of Q_1, and $Z_{cd}(s)$ is the ratio of the current entering the base of Q_1 over the current entering the bandpass filter at the input (IN), which is equal to 0.5 over the bandpass. In (3), the first term is the current gain of Q_1 at high frequency, the product of the first three terms is the output current, that is, the collector of Q_1 and so of Q_2 assuming an ideal operation of the cascode, and the last term is the output impedance at the output node. The inductor L_2 compensates the roll-off with frequency of output current by adding a zero at $R_2/2\pi L_2$. Therefore, in order to obtain a flat response over 3.1-5 GHz at the output both the zero due to L_2 and the cutoff frequency $f_o = \frac{1}{2\pi\sqrt{L_2C_{out}}}$ of the denominator of the output impedance must be pushed beyond 5 GHz. Also, this will ensure that non-linear phase shift and thus nonflat group delay due to peaking does not occur in-band. Figures 2, 3, and 4 show the simulated results of the amplifier, respectively, the smith chart of S11; the S11, S22, and S12 (in dB); and S21 and noise figure (in dB).

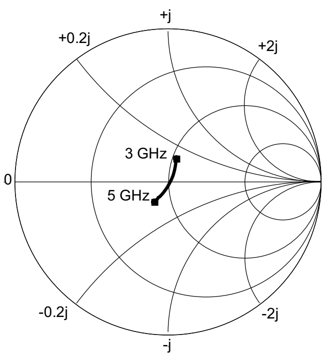

Fig. 2. Simulated S11 traces of LNA using LC-Ladder filter matching.

The power gain is 18 dB with a maximum of about 19 dB at around the center frequency or 4 GHz. This is due to the better matching around this frequency as it is clear in Figs. 2 and 3. However, the noise figure achieved here is around 4.5 dB, which is not as low as expected. In contrary to FET cascode, the condition for optimum gain is different from that of the minimum noise figure, imposing a tradeoff between gain and noise performance.

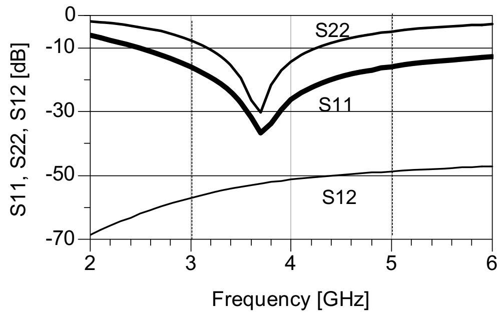

Fig. 3. Simulated input/output return loss and reverse isolation of LNA using LC-Ladder filter matching.

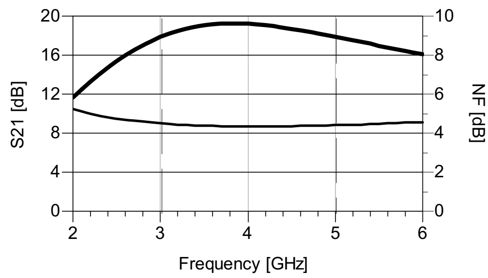

Fig. 4. Simulated power gain and noise figure of LNA using LC-Ladder filter matching.

As can be seen in Fig. 3, the simulated input return loss (S11) is higher than 17 dB over 3-5 GHz. The output return loss (S22) is higher than 5 dB due to the cascode. The reverse isolation is better than -47 dB, which is good. The inductors L_e=0.1 nH and L_b=0.1 nH can be absorbed as a part of the package parasitics during implementation. The inductor L_m=2.7 nH can be realized with a transmission line. The dc power consumed is 11 mW under 1.5 V supply. The Rollet stability factor, decreasing with frequency, was always above 2 due to a careful design of the peaking inductor L_2, which may cause instability.

III. DESIGN USING SHUNT-FEEDBACK

Figure 5 shows a schematic of the proposed LNA with a resistive shunt-feedback. The inductor L_e is added for simultaneous noise and input matching and L_b for the impedance matching between the source resistance R_S and the input of the LNA. The emitter inductance (L_e) plays the role of a series feedback and hence shifts the input impedance to higher values. This low inductance of about 0.2 nH is realizable with a transmission line, hence sparing additional areas for on-ship spiral inductor.

Top

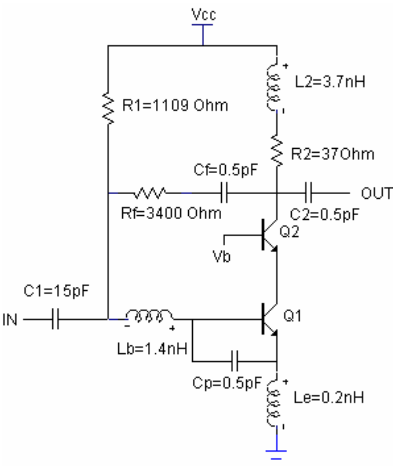

Fig. 5. schematic of a wideband amplifier using resistive shunt-feedback.

Figures 6, 7, and 8 show the S-parameters of the LNA.

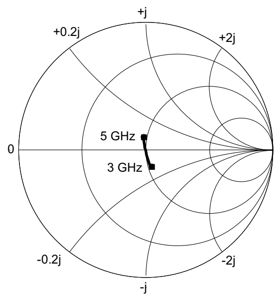

Fig. 6. Simulated S11 traces of LNA using resistive shunt-feedback.

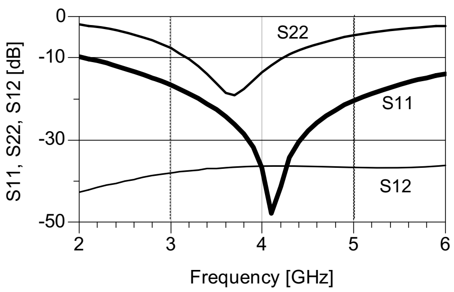

Fig. 7. Simulated input/output return loss and reverse isolation of LNA using resistive shunt-feedback.

It is clear from Figs. 6 and 7 that the feedback allowed a better impedance matching over 3-5 GHz. The Miller feedback resistor at the input reduces the quality factor of the input resonating matching network, hence widening the input match around the center frequency of 4 GHz [3]. The feedback resistance R_f = 3.4 kΩ here is high enough to not degrade the noise figure while widening enough the impedance matching.

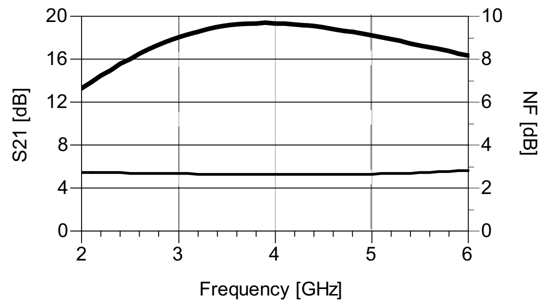

Fig. 8. Simulated power gain and noise figure of LNA using resistive shunt-feedback.

Shunt-feedback for cascode topologies may not be appropriate for the full UWB range (i.e. 3.1-10.6 GHz). Using this technique for wider range would require a significant decrease in R_f in order to lower the quality factor sufficiently, which would in turn degrade the noise factor. The power gain achieved is about 18.3 dB with a noise figure as low as 2.5 dB, input return loss better than -20 dB, output return loss higher than 5 dB. The reverse isolation is better than -34 dB. The inductors L_e=0.2 nH and L_b=1.4 nH can both be realized with a transmission line. The dc power consumed is 11 mW under 1.5 V supply. The Rollet stability factor was always above 3.

We tried also to benefit from the virtues of both wideband techniques studied above by studying an amplifier using simultaneously the LC-ladder filter matching and resistive shunt-feedback. This has not improved significantly the LNA wideband characteristics. In this case, the voltage gain becomes

$$\frac{v_{out}}{v_{in}} = \frac{-g_{m1}}{sC_t}\frac{W(s)}{R_S}Z_{cd}(s)\frac{(R_2 // R_f)\left(1+s\frac{L_2}{R_2}\right)}{1+s\left(\frac{L_2}{R_2+R_f}+(R_2 // R_f)C_{out}\right)+s^2\frac{(R_2 // R_f)}{R_2}L_2C_{out}} \tag{4}$$

The cutoff frequency of the last term in (4) becomes $f_o = \frac{1}{2\pi\sqrt{\frac{(R_2 // R_f)}{R_2}L_2C_{out}}}$, hence pushed to higher values compared with the case of LC-ladder matching without feedback. This would flatten more the output response. However, to obtain a significant flattening, R_f must be set low enough, degrading hence noise performance of the LNA.

Overall, the shunt-feedback topology gives a better performance over 3-5 GHz. Table I compares the results of the three topologies.

Table II compares the results of the shunt-feedback topology of this work with recently reported works.

TABLE I
COMPARISON OF WIDEBAND Si LNA PERFORMANCES OF DIFFERENT TECHNIQUES

Ref.	Feedback	LC-Matching	Feedback & LC-Matching
S21 (dB)	18.3±1	18.0±1.5	18.0±1.2
NF (dB)	2.5	4.5	2.6
S11 (dB)	< -20	< -17	< -12
S22 (dB)	< -5	< -5	< -5
S12 (dB)	< -34	< -47	< -32
Pdc (mW)	11.0	11.0	11.6
ICP (dBm) @ 5 GHz	-17.0	-18.5	-17.5
ICP (dBm) @ 3 GHz	-19.0	-22.5.5	-18.5
IIP3 (dBm) @ 5 GHz	-6.0	-8.5	-8.3
IIP3 (dBm) @ 3 GHz	-7.8	-11.6	-8.8

IV. CONCLUSION

Wideband low-noise amplifiers using different wideband techniques optimized for the lower-frequency band (3-5 GHz) of UWB systems are presented. The amplifiers topology adopts the LC-ladder filter matching and/or conventional resistive shunt-feedback, embedding a HBT cascode amplifier. These techniques have allowed a good input matching. A superior overall performance is obtained with the shunt-feedback technique over 3-5 GHz. The simulated result for this topology shows more than 18 dB of power gain, a higher than -29 dB of input return loss, an output return loss bigger than -5 dB, a reverse isolation better than -34 dB, and an input IP3 of -6 dB, while dissipating 11 mW from a 1.5 V supply. The noise figure stays as low as 2.5 dB over all 3-5 GHz. The proposed resistive shunt-feedback LNA shows advantages in overall performance, compared to other recently published wideband topologies.

TABLE II
COMPARISON OF FEEDBACK LNA WITH RECENTLY PUBLISHED DESIGNS

Ref.	[3]	[4]	[5]	[6]	[7]	[8]	[9]	This work
3-dB BW (GHz)	2 – 4.6	0.6 – 22	0.02 – 4.6	1 – 7	2.4 – 9.5	2 – 10	0.5 – 5.5	3 – 5
Gain (dB)	9.8	8.1	9.8	13.1	9.3	21	6.5	18.3
NF (dB)	2.3	4.3	1.9	3.3	4	2.5	5.7	2.5
S11 (dB)	< -9	< -8	< -8	< -7.2	< -9.9	-7	< -7	< -20
S22 (dB)	-	-	-	-	-	-	-	< -5
S12(dB)	-	-	-	-	-	-	-	< -34
Pdc (mW)	12.6 (only cor e LNA)	52	35	75	9 (only cor e LNA)	27 (only cor e LNA)	83.4	11.0
IIP3 (dBm)	-7	-	0	-4.7	-6.7	-5.5	-	-6 @ 5 GHz
ICP (dBm)	-	-	-	-	-	-14.7 @ 3.4-5.4 GHz	-	-17.0 @ 5 GHz
Topology	Shunt FB with inductive degeneration	Distributed (single-ended)	Feedback (single-ended)	Feedback (differential)	LC-filter based (single-ended)	LC-filter based (single-ended)	Distributed (single-ended)	Shunt FB with inductive degeneration
Technology	0.18 μm CMOS	0.18 μm CMOS	0.25 μm CMOS	0.18 μm CMOS	0.18 μm CMOS	SiGe	0.6 μm CMOS	SiGe HBT
Year	2005	2003	2002	2003	2004	2004	2000	2006

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