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A 3 to 5 GHz UWB SiGe HBT Low Noise Amplifier for WPANS IEEE 802.15.3a Standard

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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.

Key words: Low-noise amplifier, ultra wideband, wideband matching, shunt-feedback

INTRODUCTION

Although the Ultra-Wideband (UWB) standard (IEEE 802.15.3a) for WPANs 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 as suggested by Kim *et al.* (2005) and Liu *et al.* (2003). According to Bruccolori *et al.* (2002) and Andersson *et al.* (2003), the resistive shunt-feedback broadens the working frequency in terms of input impedance matching, gain and linearity. 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 as found by Ismail and Abidi (2004) and Nguyen *et al.* (2004). 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 study 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.

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.

Here, the matching circuit elements are chosen (Ismail and Abidi, 2004)

$$L_m \approx \frac{R_s}{\omega_L} \quad \text{and} \quad L_e \approx \frac{R_s}{\omega_U} \quad (1)$$

$$C_m \approx \frac{1}{\omega_U R_s} \quad \text{and} \quad C_t \approx \frac{1}{\omega_L R_s} \quad (2)$$

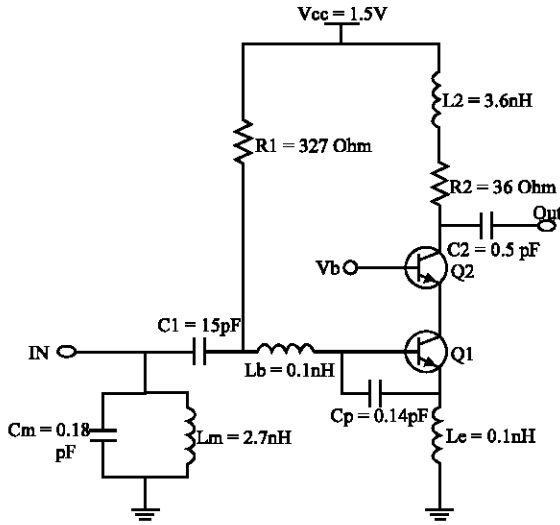


Fig. 1: Schematic of a wideband amplifier using LC-Ladder filter matching

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

$$f_o = \frac{1}{2\pi\sqrt{L_2C_{out}}}$$

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

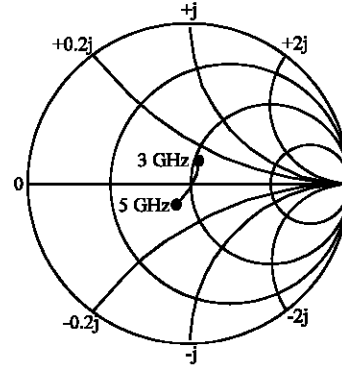


Fig. 2: Simulated S11 traces of LNA using LC-Ladder filter matching

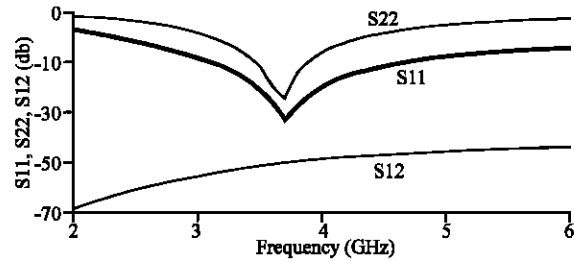


Fig. 3: Simulated input/output return loss and reverse isolation of LNA using LC-Ladder filter matching

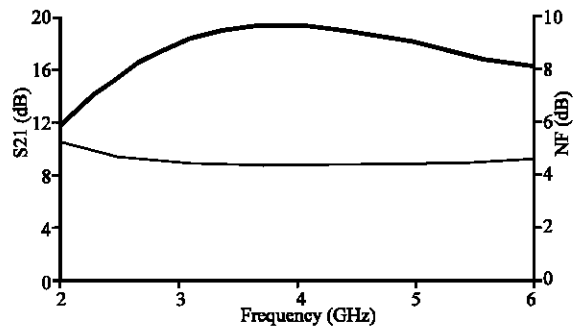


Fig. 4: Simulated power gain and noise figure of LNA using LC-Ladder filter matching

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. Figure 2-4 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).

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 Fig. 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.

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 $L_o = 0.1$ 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.

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_o 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-chip spiral inductor.

Figure 6-8 show the S-parameters of the LNA. It is clear from Fig. 6 and 7 that the feedback allowed a better impedance matching over 3-5 GHz. The Miller feedback

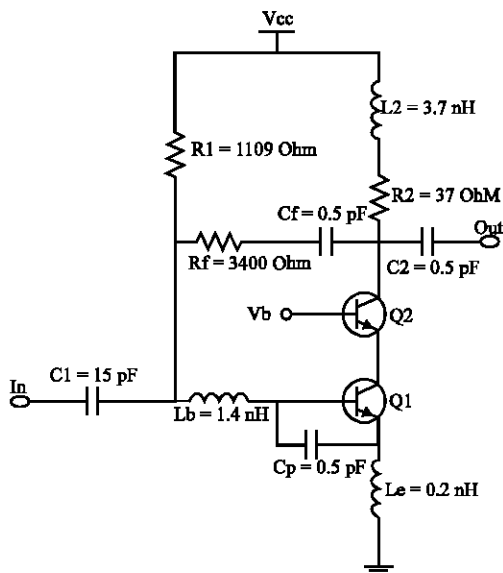


Fig. 5: Schematic of a wideband amplifier using resistive shunt-feedback

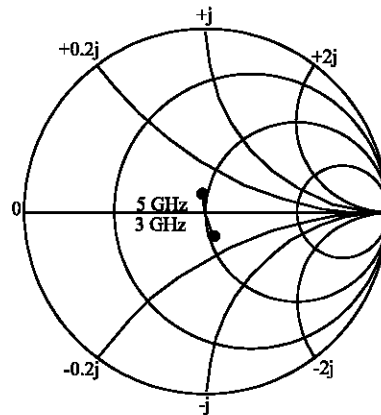


Fig. 6: Simulated S11 traces of LNA using resistive shunt-feedback

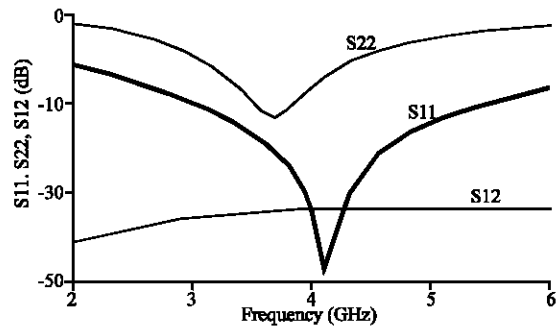


Fig. 7: Simulated input/output return loss and reverse isolation of LNA using resistive shunt-feedback

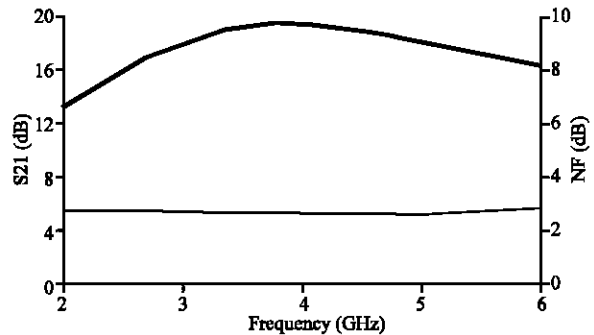


Fig. 8: Simulated power gain and noise figure of LNA using resistive shunt-feedback

Table 1: Comparison of Wideband S_r LNA Performances of different techniques

Ref.	Feedback	LC-matching	Feedback and 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

Table 2: Comparison of feedback lna with recently published designs

Ref.	(Kim <i>et al.</i> , 2005)	(Liu <i>et al.</i> , 2003)	(Bmccolori <i>et al.</i> , 2002)	(Andersson <i>et al.</i> , 2003)	(Bevilacqua and Niknejad, 2004)	(Ismail and Abidi, 2004)	(Nguyen <i>et al.</i> , 2004)	Present study
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	52	35	75	9	27	83.4	11.0
	(only core LNA)				(only core LNA)	(only core LNA)		
IIP3 (dBm)	-7	-	0	-4.7	-6.7	-5.5	-	-6@5GHz
ICP (dBm)	-	-	-	-	-	-14.7 @ 3.4 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

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 as suggested by Kim *et al.* (2005).

The feedback resistance $R_f = 3.4 \text{ k}\Omega$ here is high enough to not degrade the noise figure while widening enough the impedance matching.

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 $L_e = 0.2 \text{ nH}$ and $L_o = 1.4 \text{ nH}$ 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 study, the voltage gain becomes:

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

The cutoff frequency of the last term in (4) becomes,

$$f_o = \frac{1}{2\pi \sqrt{\frac{(R_2 // R_f)}{R_2} L_2 C_{out}}}$$

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 1 compares the results of the three topologies.

Table 2 compares the results of the shunt-feedback topology of this work with recently reported works.

CONCLUSIONS

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.

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