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Reprinted from
*Proc 2nd European Microwave Integrated Circuits Conference (EuMIC 2007),
Munich, Germany, October 8-10, 2007, pp 247-250*

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Highly Compact 3.1 -10.6 GHz UWB LNA in SiGe HBT Technology

J. Dederer, S. Chartier, T. Feger, U. Spitzberg, A. Trasser, and H. Schumacher

Institute of Electron Devices and Circuits

University of Ulm,

89069 Ulm, Germany

jochen.dederer@uni-ulm.de

Abstract— We present the design, implementation and measurement of a low noise amplifier (LNA) in a low cost $0.8\ \mu\text{m}$ SiGe heterojunction bipolar technology (HBT). The measured noise figure is between 2.1 dB and 2.6 dB in the FCC-allocated bandwidth for ultra-wideband (UWB) systems. The circuit delivers 19.6 dB peak gain with gain variations of 1.3 dB within the entire band from 3.1 to 10.6 GHz. Broadband noise and power matching has been achieved with a cascode topology using resistive shunt feedback in combination with a diode DC level shifter. The measured input IP3 is -14.1 dBm with 10.3 mA total current from a 3.5 V supply. All performance characteristics are comparable to the best reported UWB LNAs but come at a drastically smaller occupied die area of $0.13\ \text{mm}^2$.

I. INTRODUCTION

Low noise amplifiers for UWB applications require a low noise figure, high gain and a flat frequency response over the entire UWB frequency band. Additional priorities are impedance matching and linear phase response. Another challenge is the necessary dynamic range of the LNA due to the presence of in-band interferers along with a moderate power consumption. Commonly used techniques in designing broadband amplifiers are feedback, inductive and capacitive peaking methods or distributed amplification. Power consumption and necessary die area are major draw-backs of the latter. Concentrated amplifiers with lumped elements generally consume a much smaller die area. This is especially true for designs using resistive feedback due to the absence of large spiral inductors. The UWB LNA design presented here is a highly compact design based on a cascode topology with resistive feedback in combination with an emitter follower stage.

II. TECHNOLOGY

The presented circuit has been designed and fabricated using the commercially available ATMEL SiGe2-RF HBT technology [1] which is a $0.8\ \mu\text{m}$ lithography hetero-bipolar technology. The minimum electrically active emitter size of the npn transistor is $0.5\ \mu\text{m} \times 1.1\ \mu\text{m}$. A selective collector implant increases the transit frequency f_T from 50 GHz to 80 GHz at the cost of a reduced breakdown voltage BV_{CE0} from 4.3 V to 2.4 V. The process offers three metallization layers, four different types of resistors and dielectric MIM capacitors as well as nitride capacitors. The passive and active devices are realized on low-resistivity $20\ \Omega\text{cm}$ p-type substrate.

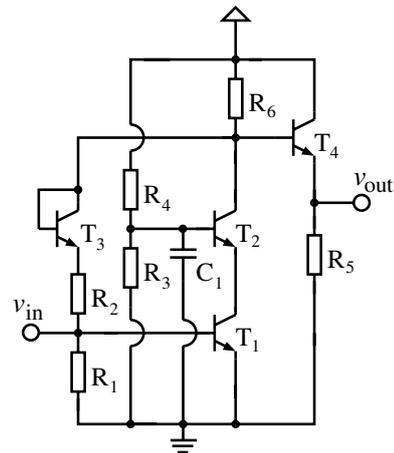


Fig. 1. Schematic of the broadband cascode LNA with resistive shunt feedback in combination with a diode DC level shifter

III. ULTRA-WIDEBAND LNA DESIGN

It is well known that the reduction of the Miller effect in cascode topologies is of major advantage for LNAs due to the typically large transistor perimeters dictated by noise-matching considerations and consequently high base-collector capacitance of the input transistor which often dominates the rolloff characteristics of the amplifier. With respect to broadband designs, the improved frequency response of the cascode compensates for the degradation in the minimum achievable noise figure F_{\min} compared to a single common emitter stage. Typical narrow band cascode designs use a combination of series inductive feedback and a series inductance at the input for simultaneous noise and power matching. The series inductive feedback shows up as a real resistance at the input whereas the series inductance adjusts the imaginary part of the cascode input impedance by simultaneously moving the optimum source reflection coefficient $\Gamma_{S,\text{opt}}$. Broadband designs combine this approach with resistive feedback between the base of the input transistor and the cascode output. Previously published work on broadband cascode LNAs includes a SiGe HBT LNA with an additional shunt base-emitter capacitance and inductive peaking [2]. Although the inductor sizes have been significantly reduced compared to earlier presented work on UWB LNAs, the major part of the occupied die area

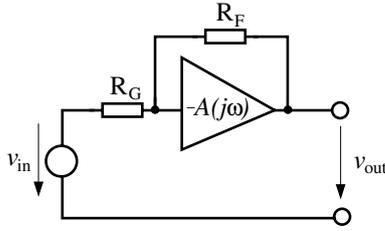


Fig. 2. Simplified model of amplifier with negative feedback

is still determined by inductors. The LNA presented here incorporates a cascode topology with a drastically smaller occupied die area due to the absence of inductors. Broadband operation in terms of noise performance, flat gain response, bandwidth and power matching has been achieved with a simple resistive shunt feedback in combination with a diode DC level shifter which improves the large signal behavior of the design. The DC level shifter in the shunt feedback uses the base emitter diode of transistor T_3 which is biased via resistors R_1 and R_2 as shown in Fig. 1. The output buffer is an emitter follower stage which provides broadband $50\ \Omega$ match to the output. Generally speaking, negative feedback exchanges gain for bandwidth. In a first approximation the bandwidth enhancement and gain reduction of the cascode with feedback compared to the cascode without feedback can be derived from a simple model as shown in Fig. 2. The model presupposes infinite input impedance of the open loop amplifier and a frequency dependent voltage gain $A(j\omega)$ which is described with a single-pole rolloff

$$A(j\omega) = \frac{A_0}{1 + j\frac{\omega}{\omega_0}} \quad (1)$$

where A_0 is the open loop DC voltage gain and ω_0 is the open loop cutoff frequency. Based on these simplifications, the closed loop voltage gain of the LNA is approximated with

$$\frac{v_{out}}{v_{in}} \approx -\frac{A_0 \cdot R_F}{R_F + (A_0 + 1) \cdot R_G} \cdot \frac{1}{1 + j \cdot \frac{\omega}{\omega_0'}} \quad (2)$$

where the improvement in bandwidth is expressed by the closed loop cutoff frequency ω_0' with

$$\omega_0' = \omega_0 \left(1 + \frac{A_0 \cdot R_G}{R_G + R_F}\right). \quad (3)$$

In the relevant frequency range the diode in the shunt feedback path can be considered as purely resistive with a resistance of approximately $95\ \Omega$ which adds to R_2 to an overall $645\ \Omega$ feedback resistance R_F . According to (3), the feedback resistance R_F improves the cutoff frequency $\frac{\omega_0'}{2\pi}$ to 13 GHz compared to the open loop amplifier with a simulated cutoff frequency $\frac{\omega_0}{2\pi}$ of 4 GHz for a given $50\ \Omega$ source impedance R_G and a simulated DC voltage gain A_0 of 29.9 dB. The latter is determined for a load impedance given by the input resistance of the succeeding emitter follower stage. Based on (2), the closed loop DC voltage gain is approximated with

$$\frac{v_{out}}{v_{in}} \approx -\frac{A_0 \cdot R_F}{R_F + (A_0 + 1) \cdot R_G} \approx -8.93 \hat{=} 19.0\ \text{dB}. \quad (4)$$

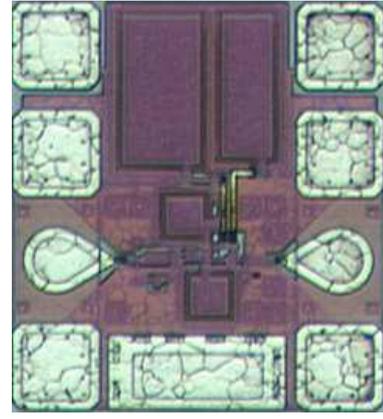


Fig. 3. Microphotograph of the UWB LNA

The main noise contributor to the overall noise figure is transistor T_1 (Fig. 1) which has been sized as a compromise between optimum current density for minimum noise and achievable bandwidth. The effective emitter window of T_1 has a size of $0.5\ \mu\text{m} \times 19.7\ \mu\text{m}$. The collector-base-emitter-base (CBEB) configuration with two base contacts reduces the critical base series resistance which negatively affects the noise performance and the maximum frequency of oscillation. A microphotograph of the chip is shown in Fig. 3. The complete chip, pads included, has the extremely small chip size of $0.34\ \text{mm} \times 0.38\ \text{mm}$. The large area consumed by the bonding pads has to be considered as a receiver of substrate noise. To avoid this, the lowest available metal layer of the technology was placed under the signal pads providing a shielding which makes the bond pads act purely reactive [3]. The additional rectangular ground pad at the lower edge of the chip allows multiple bond wires which provide low-impedance ground connections when mounting the amplifier. This is necessary as no backside metallization and no through-substrate via holes are available.

IV. MEASUREMENT RESULTS

Measurements were performed on-wafer in a $50\ \Omega$ test environment using a vector network analyzer. Two on-wafer ground-signal-ground microwave probes were used to contact the input and output ports of the circuit. The amplifier is biased with 10.3 mA from a 3.5 V supply. Fig. 4 depicts the measured gain. The LNA shows 19.6 dB peak gain with gain variations of 1.3 dB within the UWB frequency band. The measured $-3\ \text{dB}$ cutoff frequency is 12.9 GHz. Both, measured gain and measured bandwidth are similar to the calculated values given by a first approximation according to (2) and (3). Excellent input matching across the band with a maximum value of $-8\ \text{dB}$ at the upper band edge has been achieved as shown in Fig. 5. The range where the input return loss is better than 10 dB will extend to the upper band edge for an appropriately chosen bonding inductance at the RF input by only marginally affecting the noise performance. The measured output return loss is better than 9 dB in the band of interest. Reverse isolation is better than 37 dB across the 3.1 to 10.6 GHz band. The

TABLE I
COMPARISON AND SUMMARY

Technology	Worst-case NF [dB] (BW-GHz)	Chip area [mm ²]	Gain [dB] (BW-GHz)	S ₁₁ [dB] (BW-GHz)	P _{DC} [mW]
0.8μm SiGe HBT (this work)	2.6 (3.1-10.6)	0.13	19.0 ± 0.7 (3.1-10.6)	S_{11,max} < -8 (3.1-10.6)	36.1
0.13μm CMOS [5]	2.9 (3.0-11)	0.87	15.1 ± 1.4 (3.1-10.6)	S _{11,max} < -9.9 (3.1-10.6)	9
0.18μm SiGe HBT BiCMOS [2]	3.1 (3.0-10.0)	0.72	20.3 - 3.5 (3.0-10.0)	S _{11,max} < -7.2 (3.0-10.0)	26 (without buffer)
0.8μm SiGe HBT [6]	3.2 (3.1-10.6)	0.17	23.5 - 0.6 (3.1-10.6)	S _{11,max} < -8.5 (3.1-10.6)	55
0.18μm SiGe BiCMOS [7]	3.3 (2.0-10.0)	0.88	13 - 3 (2.0-10.0)	S _{11,max} < -7 (3.0-10.0)	9.6
0.18μm SiGe BiCMOS [8]	4.2 (3.0-10.0)	1.8	21 - 4 (3.0-10.0)	S _{11,max} < -9.0 (3.0-10.0)	30
0.18μm SiGe BiCMOS [9]	4.5 (3.0-10.0)	0.52	20 ± 1 (3.0-10.0)	S _{11,max} < -10.0 (3.0-10.0)	42.5

measured 50Ω noise figure is depicted in Fig. 6. The circuit exhibits an outstanding noise performance with noise figures between 2.1 dB and 2.6 dB across the full UWB bandwidth.

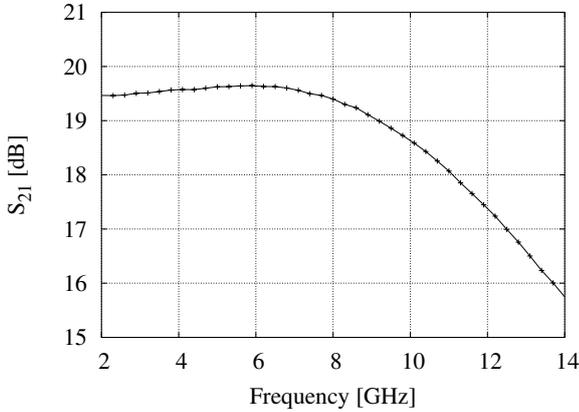


Fig. 4. Measured gain

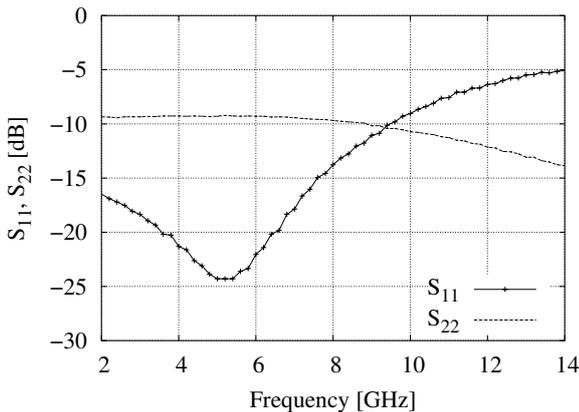


Fig. 5. Measured input (S_{11}) and output (S_{22}) scattering parameters

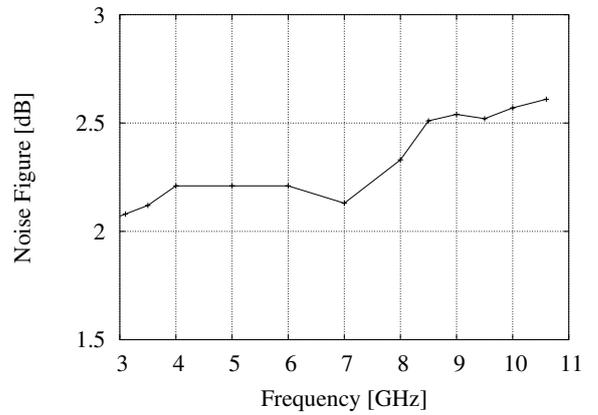


Fig. 6. Measured noise figure

Single-band 3.1 to 10.6 GHz UWB amplification requires an almost linear phase response over the full band which is not

delivered by designs using excessive peaking techniques. As shown in Fig. 7, an almost linear phase response has been achieved in a frequency range exceeding the UWB band. The average group delay is 27 ps with maximum and minimum values of 31 ps and 23 ps, respectively. Suitability for pulse-based single band UWB applications is demonstrated by the amplification of an UWB pulse with a pulse shape similar to the fifth derivative of the Gaussian bell shape [4]. The corresponding power spectral density of the pulse is centered in the UWB frequency band and makes efficient use of the allocated spectrum mask. Fig. 8 compares the measured input and output waveforms, normalized to equal maximum amplitude. Excellent pulse symmetry has been maintained. Amplifier linearity is evaluated by measuring the 1-dB compression point and the third-order intercept point. Measurements are done using a conventional setup using RF sources and spectrum analyzer. The measured input-referred third-order intercept point (IIP3) at 6 GHz (200 MHz tone-spacing) equals -14.1 dBm whereas the measured input 1-dB compression point at 6 GHz is -24.8 dBm. The linearity is mainly determined by the biasing of the emitter follower stage which has been chosen as a compromise between moderate power

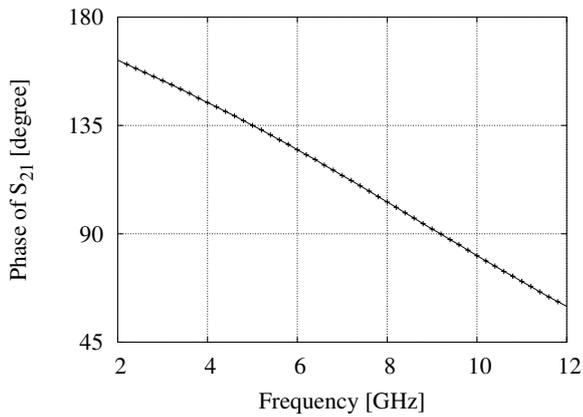


Fig. 7. Measured phase delay versus frequency

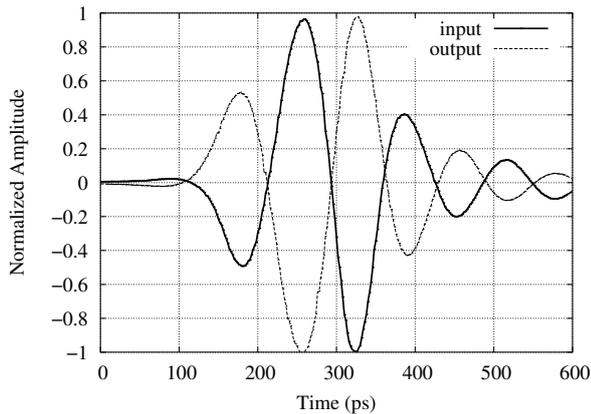


Fig. 8. Measured input and output waveforms normalized to equal maximum amplitude

consumption and linearity. Table I compares the LNA designed in this work with the best reported UWB LNAs realized in bipolar and CMOS technologies. Outstanding noise performance together with the smallest reported occupied die area has been achieved.

V. CONCLUSION

A cascode UWB low noise amplifier fabricated in a commercially available $0.8\ \mu\text{m}$ SiGe HBT technology has been presented. The design approach has been discussed with analytical equations for amplifier gain and bandwidth which have been derived from a simplified model of an amplifier using negative shunt feedback.

The design exhibits noise figures between 2.1 dB and 2.6 dB across the UWB frequency band from 3.1 to 10.6 GHz. Resistive feedback in combination with a diode DC level shifter has demonstrated simultaneous broadband noise and power matching in the absence of on-chip inductors. The presented performance parameters are comparable to the best reported UWB LNAs but come at a drastically smaller occupied die area. The low-cost technology together with the achieved shrink in occupied die area give a significant cost advantage compared to previously published work on UWB amplifiers and make the LNA an ideal candidate for a large variety of UWB applications.

ACKNOWLEDGMENT

The authors wish to thank ATMEL Germany Heilbronn for the excellent support. The work was financially supported by the German Research Foundation (DFG) project UKoLoS.

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