A Highly Compact SiGe HBT Differential LNA for 3.1-10.6 GHz Ultra-Wideband Applications

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***Abstract*—A fully differential low noise amplifier (LNA) using SiGe HBT technology for ultra-wide band applications is presented. Measured results show the maximum power gain of 19.9 dB with a variation of 1.8 dB within the entire band, the noise figure is between 2.1 dB and 2.9 dB in the FCC-allocated UWB band from 3.1-10.6 GHz. The input 1-dB compression point is -17.5 dBm measured at 7 GHz. All measured results show excellent agreement with the simulated ones. The total current consumption is 22 mA from a 3.5 V supply. The inductor-less design occupies a chip size of only 0.14 mm^2 including bond pads.**

I. Introduction

Ultra-wideband (UWB) technology is developed for high speed communication, location and sensing applications [1]. The Federal Communications Commission (FCC) was first to regulate UWB systems by allocating the 3.1-10.6 GHz band with a maximum power spectral density (PSD) of -41.3 dBm/MHz. Other administrations, e.g. in Europe and Japan, issued their own, more restrictive, frequency allocations, which however are within the FCC mask, which remains therefore a good choice for general purpose UWB components such as low-noise amplifiers.

The low emitted power density increases the difficulty of designing UWB receivers. As the first stage of a receiver front-end, the UWB LNA should provide low noise figure, high gain and flat frequency response over the whole UWB frequency band. Additional priority is the group delay variation which determines pulse distortion in time-domain. Several techniques have been reported to achieve these goals, e.g. distributed amplifiers [2] and resistive feedback [3].

This paper presents a fully differential LNA, using resistive feedback, and avoiding any spiral inductors, with a highly competitive noise figure. Differential circuit topologies are highly advantageous for UWB circuits because differentially fed antennas avoid radiation from the outer shield of unbalanced feed lines. The cleanest solution is to mount a differential receiver frontend directly at the feedpoint of a symmetrically fed antenna. Additional advantages of fully differential designs are ease of packaging due to the creation of on-chip grounds decoupling common-mode connections such as supply voltage and ground, and the cancellation of even-order nonlinear distortions. At the downside, differential configuration increases circuit complexity and power consumption, and measurements are more difficult. The proposed differential LNA here is based on cascoded emitter-coupled pair with resistive feedback. It has a very small die area of 0.14mm^2 by avoiding large on chip spiral inductors.

II. Technology

The presented circuit is designed for and fabricated with the Telefunkon Semiconductors GmbH SiGe2RF 0.8 μm HBT technology. The technology offers two different npn transistor types (f_T=50 GHz, BV_{CEO}=4.3 V and f_T=80 GHz, BV_{CEO}=2.4 V with a selective collector implant), both with f_{max}=80 GHz. This technology incorporates three metal layers, four types of resistors, MIM as well as nitride capacitors. All the devices were fabricated on a low resistivity 20 Ωcm substrate.

III. Circuit design

Fig. 1 shows the schematic of the differential LNA. It consists of an emitter-coupled pair with cascoded devices, followed by two emitter follower stages as buffers. A current mirror is used to bias the cascode stage. Input and output are differential as the LNA will be connected to a symmetrical

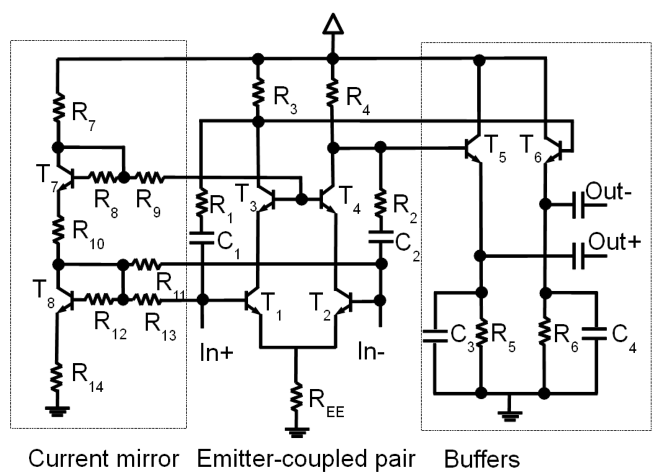

Fig. 1. Schematic of the proposed fully differential LNA.

antenna, and shall feed a Gilbert cell type analog multiplier directly, without an unbal circuit. The symmetry of the emitter-coupled pair is achieved by placing identical transistors and passive components in the two branches. The resistor R_{EE} works as the current source of the emitter-coupled pair, providing significant common-mode rejection.

In this paper, the circuit performance in differential mode is considered. The emitter-coupled pair consists of two half-circuits, which can be clearly seen in Fig. 1. Only the left half-circuit of the emitter-coupled pair will be discussed here, since the right part is identical to the left one. T_1, in common emitter configuration, and T_3 in common base topology form the cascode. The primary reason of the cascode configuration is to reduce the Miller effect at the input of transistor T_1, increasing the bandwidth. The shunt-shunt feedback (R_1 and C_1) further broadens the bandwidth and improves the input matching simultaneously. Although R_1 does contribute thermal noise to the input node, the main noise contributor to the overrall circuit is transistor T_1. In general, noise figure F of an arbitrary two-port can be expressed as a function of minimum achievable noise figure F_{min}, normalized equivalent noise resistance r_n, the source reflection coefficient Γ_S, and the noise-optimum source reflection coefficient $\Gamma_{S,opt}$ with

$$F = F_{min} + \frac{4r_n|\Gamma_S - \Gamma_{S,opt}|^2}{(1 - |\Gamma_S|^2)|1 + \Gamma_{S,opt}|^2}, \tag{1}$$

where r_n is the normalized value of the equivalent noise resistance R_n with

$$r_n = \frac{R_n}{Z_0}, \tag{2}$$

where Z_0 is the reference impedance. According to [4], $|\Gamma_{S,opt}|$ and r_n will be decreased with increasing transistor size and thus makes noise matching easier. In this design, careful selection of input transistor size and adjusting the bias point were done as a compromise between optimum current density for minimum noise figure, noise-matched input impedance and achievable bandwidth. The emitter size of T_1 is chosen to be $0.5\,\mu\mathrm{m} \cdot 24.7\,\mu\mathrm{m}$ and the emitter current is 5 mA. A negligible penalty, with a maximum value of 0.2 dB, is achieved within the entire band for not achieving noise match exactly. The wide band noise and input power match were accomplished by selection of input transistor with suitable biasing and shunt-shunt resistive feedback.

The two emitter follower buffers work as impedance converters. They provide high input impedance for a good inter-stage matching and lower output impedance for the output matching issues. The emitter degeneration capacitors are used to improve the buffer bandwidth. As a compromise between power consumption and linearity, each emitter-follower consumes a current of 5.8 mA. The buffer stages can be removed when fed to a Gilbert cell type analog multiplier in the correlation receiver-front end design, which will significantly decrease the power consumption. The microphotograph of this differential LNA is shown in Fig. 2. This layout was designed to be highly symmetric to maintain the balancing advantages of a differential configuration. The symmetry is obtained by a suitable arrangement of all the components and increasing the length of the DC feed line to obtain the same number of crossings between each signal and the DC path. This chip has an extremely small size of $0.37 \cdot 0.38\mathrm{mm}^2$ including all bound pads. The lowest available metal layer was placed below the large-sized bonding pads to provide a ground shield, as otherwise noise figure may be deteriorated by substrate noise pick-up.

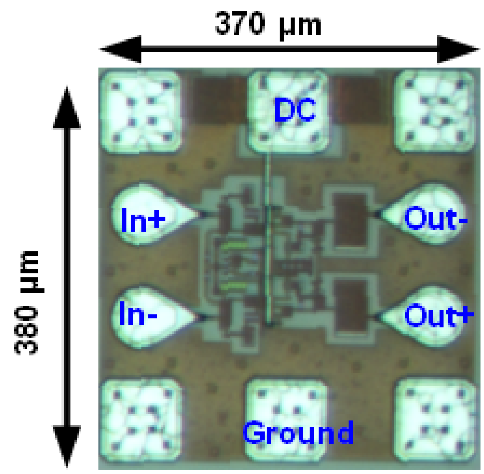

Fig. 2. Microphotograph of the differential UWB LNA.

IV. Measurement Results

The measurements were performed on wafer using microwave ground-signal-signal-ground (GSSG) probes with 100 μm pitch. Differential S-parameters were measured using a

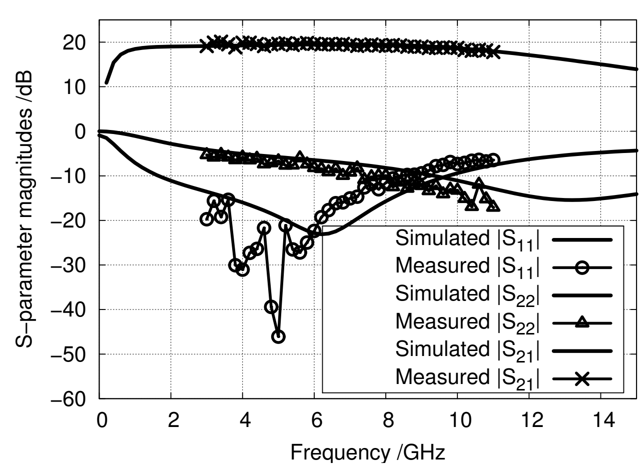

Fig. 3. Measured and simulated S-parameter magnitudes of the differential LNA.

vector network analyzer together with two identical passive microstrip line UWB baluns. The influence of the baluns is removed during the calibration process. The measurement was

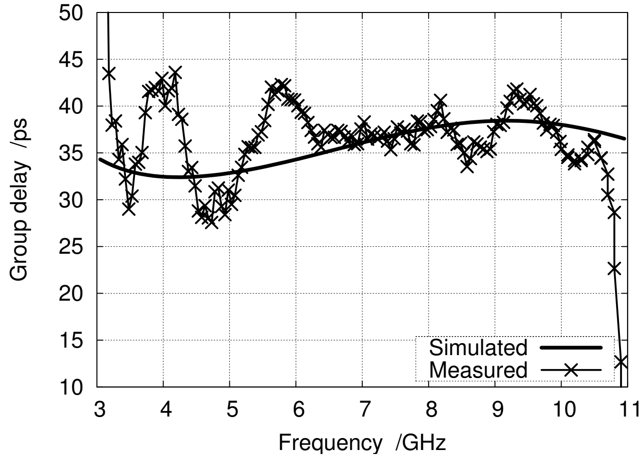

Fig. 4. Measured and simulated group delay versus frequency.

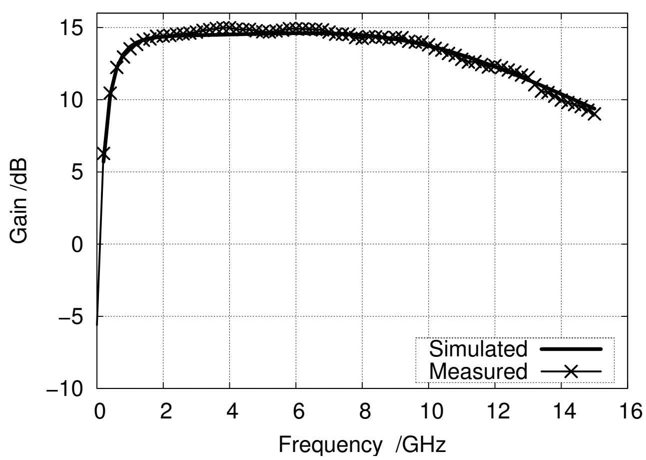

Fig. 5. Measured and simulated single-ended gain.

performed from 3 to 11 GHz because of the operating range of the UWB baluns. Fig. 3 shows the measured and simulated S-parameters. Some ripples generated in the measured curves are from the non-ideal UWB balun performance. The LNA shows a differential gain of 19.9 dB gain with a 1.8 dB variation in the whole UWB frequency band from 3.1 to 10.6 GHz. Input return loss is smaller than -7 dB, and the output one has a value of smaller than -6 dB in the complete frequency range. Small group delay variation is required for single-band 3.1 to 10.6 GHz impulse radio UWB purposes. As shown in Fig. 4, the measured group delay variation is smaller than 15 ps within the entire band. To investigate the 3-dB bandwidth, a single-ended measurement from port out- to in+ was measured with the other ports terminated by 50 Ω resistors. The circuit was then re-simulated to obtain S-parameters for this particular single-ended configuration. The information of single-ended S_{21} is shown in Fig. 5. It becomes clear from Fig. 3 and Fig. 5 that both the measured single-ended and differential S_{21} are extremely close to the simulated ones. The 3-dB bandwidth of this LNA can be concluded as from 0.6 to 12.6 GHz.

This paper uses the method in [5] to extract the differential noise figure from the single-ended measurements. First the single-ended noise figure F_{31} with the same set-up as described for the single-ended gain measurement was done. Then, after measuring the transducer gain from port out- to in+ (G_{31}) and out+ to in+ (G_{32}), due to the symmetry of the differential LNA, the differential noise figure can be extracted as

$$F_{diff} = 1 + \frac{1}{G_{31} + G_{32}}(F_{31}G_{31} - G_{31} - G_{32}). \quad (3)$$

Fig. 6 shows information of all the noise figures. Both the measured single-ended and extracted noise figures show very good agreement with simulation ones. The differential noise figure varies from 2.1 to 2.9 dB across the whole band.

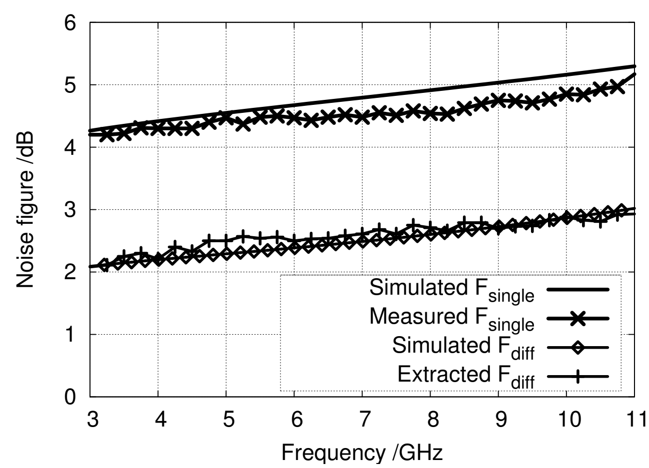

Fig. 6. Measured single-ended and extracted differential noise figures together with simulated ones.

The linearity of this amplifier was measured by the 1-dB compression point. Fig. 7 shows the large signal behavior of the amplifier. The measured input 1-dB compression point at 7 GHz is -17.5 dBm. The LNA draws a DC current of 22 mA from a 3.5 V supply. However, the power consumption can be drastically reduced if the buffer stages are removed while feeding a Gilbert cell multiplier directly. The overall performance of a broadband LNA can be expressed by the means of the figure of merit (FOM), which is defined through maximum gain G_{max}, 3-dB bandwidth BW, average noise figure F_{avg}, and dissipated power P_{diss} [6],

$$FOM = \frac{G_{max}BW}{(F_{avg} - 1)P_{diss}}, \quad (4)$$

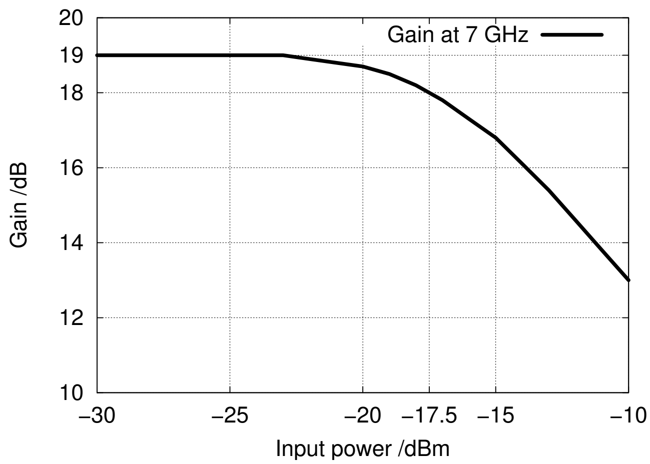

Fig. 7. Measured gain of the LNA depending on input power.

TABLE I
COMPARISIONS WITH PUBLISHED DIFFERENTIAL UWB LNAS

Technology	Worst-case NF [dB](BW-GHz)	Area [mm^2]	FOM [GHz/mW]
0.8 μm SiGe HBT (this work)	**2.9 (3.1-10.6)**	**0.14**	**2.0**
0.25μm SiGe:C BiCMOS Datta [7]	5.5 (3.1-10.6)	0.9	1.7
90 nm CMOS Pepe [8]	6.5 (3.1-10.6)	0.685	< 1
0.13 μm CMOS * Gharpurey [9]	5.7 (2-5.2)	0.24	0.3

*: single-ended input and differential output.

where G$_{max}$ and F$_{avg}$ are linear values. However gain flatness and group delay variation which are as well important parameters for UWB amplifiers are not included. Table I shows the comparisons between the proposed LNA with some excellent published differential UWB LNAs. It shows that the presented LNA occupies a very small area and achieves a higher value of FOM compared to the two fully differential LNAs in [7] and [8], which means a better overall performance. The presented IC has the lowest worst case noise figure of all differential low-noise amplifiers for FCC-mask UWB applications reported to far in the literature, on par with the best single-ended UWB LNAs on Silicon [3].

V. CONCLUSION

A fully differential UWB LNA fabricated by 0.8 μm SiGe HBT has been presented. It shows a noise figure between 2.1 dB and 2.9 dB from 3.1 to 10.6 GHz. The measured gain shows a maximum gain of 19.9 dB with a 1.8 dB variation in the whole band, and a 3-dB bandwidth of 12 GHz is achieved. The group delay variation is smaller than 15 ps in the entire frequency range. The input 1-dB compression point is -17.5 dBm measured at 7 GHz. Due to a circuit topology completely avoiding spiral inductors, the differential circuit occupies an extremely small die area of 0.14 mm^2.

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