A New Application of Current Conveyors: The Design of Wideband Controllable Low-Noise Amplifiers

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Abstract. *The aim of this paper is three-fold. First, it reviews the low-noise amplifier and its relevance in wireless communications receivers. Then it presents an exhaustive review of the existing topologies. Finally, it introduces a new class of LNAs, based on current conveyors, describing the founding principle and the performances of a new single-ended LNA. The new LNAs offer the following notable advantages: total absence of passive elements (and the smallest LNAs in their respective classes); wideband performance, with stable frequency responses from 0 to 3 GHz; easy gain control over wide ranges (0 to 20 dB). Comparisons with other topologies prove that the new class of LNA greatly advances the state of the art.*

Keywords

All-transistor circuits, low-noise amplifiers, multi-band receivers, wideband RF circuits.

1. Introduction

Wireless communications receivers are designed according to specifications corresponding to a particular standard. However, to be truly mobile, a receiver must be able to treat several standards simultaneously. Thus, the development of wideband radio-frequency (RF) front-end topologies is necessary and hinges on the development of circuits whose frequency characteristics are stable over several gigahertz and whose impedances are matched over wide bands [1].

The low-noise amplifier (LNA), one of the essential components, is the subject of this paper. Section 2 introduces the LNA. Section 3 elucidates the major topologies used in LNA design: single-transistor, cascode-based and two-stage. In section 4, we describe the founding principle of a new class of low-noise amplifiers based on current conveyors. Section 5 presents a new LNA solution. We start with descriptions of the fabricated circuits, measurement techniques, measured performances. The final solution is wideband and allows gain control. Thereafter, we present comparisons with existent solutions to highlight the advantages of the new class of LNAs. The paper will end with some concluding remarks (Section 6).

2. The Low-Noise Amplifier

The main role of the LNA is to enhance the level of the signal incident on its input, without introducing significant noise and distortion. As the first real signal processing element after the antenna, the LNA determines the noise and linearity performance of the overall system. It is the most sensitive block in a typical RF receiver [3]-[5].

2.1 LNA Parameters

The five fundamental parameters of LNAs are gain and bandwidth, noise, linearity, impedance matching and power consumption [3], [6]-[8]. The goals in LNA design include minimizing its noise figure, providing moderate to high gain with sufficient linearity, and establishing compatibility to other transceiver blocks (impedance matching). The additional constraint of low power consumption is imposed in portable systems.

The gain provided by the LNA is generally defined in terms of the power gain ($S_{21} = P_{OUT}/P_{IN}$), expressed in decibels by $S_{21,dB} = 20\log_{10}(S_{21})$. Most LNAs are narrow-band, but wideband circuits are gaining in importance because transceivers tend increasingly to be multi-mode and multi-standard. The noise figure of the LNA is of prime importance. Since the LNA is the first component in this cascade, its noise figure adds directly to the overall noise. Therefore, in order to reduce the total noise of the receiver, the LNA should present the lowest possible noise.

The input power of wireless standards extends over a wide range (in GSM, for example, the received signal lies from -110 dBm to -20 dBm). The LNA should be able to receive and treat this entire range. However, because of the saturation of transistors, the gain saturates at high input power. The LNA should be linear up to powers beyond the highest power likely to enter it. The 1 dB compression point, generally referred to the input (IP_{1dB}), is the power at which the gain of the LNA drops 1 dB below its steady linear value.

Another indicator of linearity is the 3rd-order intermodulation product. Wireless standards consist of several narrow receive channels. A strong blocker may be present in the channel adjacent to the one which has to be treated.

This blocker interferes with the main power tone, leading to “intermodulation products”. This may saturate the LNA and block the receiver. In carrying out intermodulation measurements on the LNA, two tones (the first desired and the second is the blocker) are applied to the input. The spacing between these tones differs according to the standard, varying from 1 MHz in GSM [10], 2 MHz in WCDMA [11], to 200 MHz in UWB [12]-[14]. A linear LNA can alleviate performance requirement of the other blocks and thus lead to low power consumption and less silicon area of the overall receiver [15].

The ports of the LNA should present impedances matched to desired values. Generally, the standard 50Ω impedance has been adopted [16]. Impedance matching is important to avoid signal reflections on a cable or alterations of the characteristics of the pre-select filter which is sensitive to terminating impedances [17], [18]. Input matching is always required; output adaptation is necessary when the LNA drives an external image-reject filter. In integrated receivers where the image filter is driven by the antenna, the LNA can be directly connected to the mixer and no output matching is required [3]. Generally, input matching determines the LNA’s. Output match effects linearity [3], [5], [16].

It is impossible to design a LNA which provides peak performance for all the five parameters; trade-offs are inevitable. To reduce the receiver noise, the LNA’s NF has to be low and its gain high (to reduce noise contributions from succeeding blocks). Since the noise figure of a transistor is inversely proportional to its collector current I_C, I_C can be raised indefinitely to reduce noise figure. However, high I_C entails higher consumption [19]. Sometimes, the linearity of the receiver is dominated by the stages which follow the LNA; in such cases, the primary goal is to minimize the power consumption for the required noise figure [7]. Moreover, high gain in the gigahertz range deteriorates the IIP3 [3]. A high gain is thus not always desired [20].

2.2 LNA Specifications

Reviews of the specifications of various standards and of the performance of existent LNAs allowed us to establish the expected LNA performance for each standard. Conventional narrowband LNAs should provide peak performance at the frequency for which they are designed. Wideband LNAs, on the other hand, should give stable performance over several hundreds of megahertz.

The LNA gain in GSM is required to be moderate, to minimize distortion and interference. The emphasis on noise figure is moderate but linearity requirements are strict [10], [20]-[23]. In GPS, on the other hand, both the gain and the noise figure have to be extremely good, 20 dB and 1 dB, respectively, whereas linearity is a secondary concern [24]. In PCS systems, the LNA should give moderate gain and high linearity [21], [25]. The linearity requirement in WCDMA is even more strict [11], [26]: IIP3 ~ 0 dBm with low consumption (<5 mA) is the major challenge. WLAN LNAs requirements are less strict: moderate gain and NF while allowing higher consumption (~10 mA) [25], [27].

In wideband LNAs, the stringency of linearity and noise performance is exchanged for a wide bandwidth and moderate performance. The replacement of three or four narrow-band LNAs by one wideband one allows for economies of power, area and cost. The gain of high-bandwidth LNAs are generally high, and the noise figure is required to be of the order of 3 dB [13], [17].

3. Existing LNAs

The topologies used are essentially similar for single-ended and differential LNAs. Differential LNAs are realized by duplicating the single-ended circuit and can moreover be analyzed and explained using their single-ended counterparts [4], [28]. We were able to divide existent LNA solutions into three distinct categories: single-transistor, cascode-based and two-stage solutions.

3.1 One-Transistor Solutions

The simplest realization of an amplifier is the common-emitter or common-source amplifier. It is inherently narrow-band because the input matching (inductors placed at the base and emitter) can only be resonated at one frequency. Output matching is obtained by the load resistor. The biggest shortcoming of this simple solution is the difficulty of simultaneously matching the port impedances for optimum power and minimum noise. The use of feed-back using a transformer and degeneration inductor allows simultaneous matching for noise and power while maintaining the same gain. Reverse signal isolation and stability are improved while still functioning at very low supply voltages [10]. Resistor R_L of Fig. 1a can be replaced by a LC-tank. This, combined with inductive degeneration, allows conjugate noise and power match. Some of the output signal is fed back to the input to further improve the input match [29].

The topologies presented above are narrow-band: the input and output are matched at the frequency where the LC circuits resonate. The bandwidth can be increased by adding a bank of output capacitors. The noise and linearity of the narrow-band version are maintained. The presence of the output L and the capacitors C_1, C_2, etc. gives rise to a circuit whose impedances are matched at various frequencies, depending on which LC combination is turned on. This is a programmable configuration which, however, is not wide-band [30]. A purely resistive feed-back can also provide wideband matching [31]. The improvement in the matching bandwidth comes at the cost of a greatly increased noise figure and high supply voltages. Feedback through a transformer can be used to ease impedance matching [28].

3.2 Cascode-Based LNAs

The single-transistor topologies presented above all benefit from simplicity and a low number of components. Their biggest drawback is the difficulty of matching impedances for lowest noise and best power transfer. Second among the drawbacks is the low isolation to signals traversing the amplifier in the direction opposite to that intended. The cascode, which uses the common-emitter/source amplifier with another (cascode) transistor, is the most widespread realization of LNAs. The presence of the additional transistor renders the input and output matching networks independent of each other.

In the basic cascode, input impedance matching is achieved using the degeneration inductor [6], [25], [26], [32], [33]. The output matching circuit is an LCR-type. One variation of this matching uses a parallel combination of the elements [34]. Another entirely foregoes the resistor and the capacitor, using only an inductor to match the output [19]. Alternatively, the output capacitor can be replaced by a capacitive divider to increase gain [24], [26]. Active post-distortion can also be used to increase linearity of the LNA [15]. A second common-collector/drain stage is sometimes added to achieve better output match and increase the gain and linearity [13].

To alleviate the need for a high supply voltage, a folded-cascode is sometimes used. The rail-to-rail voltage needed for the LNA is the same as that needed to bias one transistor (and not two, as in the conventional cascode). This allows operation at sub-1V supplies [21]. The LC tank's quality factor determines the characteristics of the LNA. The loss of some amount of current in this tank means that the gain of the folded-cascode is lower than that of the standard cascode. Moreover, the reduction in the supply voltage is somewhat negated by the increase in current dissipation.

The addition of a load on the first transistor of the classic cascode allows current reuse. This load is realized using an inductor [35] or parallel RC combination [4], [16]. The matching bandwidth of the classic cascode can be increased by employing a more evolved matching network: combining the cascode configuration with a three-section bandpass-filter based matching [12]. An alternative to the complicated filter matching is to use resistive feedback [14]. The result is a wideband input matching with small NF degradation.

Distributed amplifiers are constructed using a series combination of classical cascode amplifiers. The stages share a common biasing circuit, and the gain can be controlled by switching on the desired number of stages. The transmission lines which connect the stages provide wideband matching [36]. Alternatively, the input and output capacitances of the transistors are combined with on-chip inductors to form pseudo transmission lines with properties similar to real lines [8]. Theoretically, the gain can be increased indefinitely by adding more stages while maintaining the bandwidth. However, in practice, area constraints and passive losses limit the number of stages. Advantages offered by distributed LNAs include good gain control, broadband frequency response and good matching. However, the presence of several unitary cascode LNAs means that the noise figure, area and power consumed are increased proportionally to the gain of the LNA.

3.3 Two-stage LNAs

The simplest two-stage realization consists in a common-emitter input cascaded with a similar stage [37]. A feed-forward noise-canceling technique can be used to increase the bandwidth. This also allows for simultaneous noise and impedance matching, while canceling the noise and distortion contributions of the matching device [17].

3.4 Special Topics in LNA Design

From the presentation of various LNAs, it can be observed that wideband LNAs are dominated by two topologies: resistive feedback and distributed amplifiers. The feedback LNAs' matching is limited to higher frequencies because of parasitic capacitances [12]. The use of the transmission lines in distributed LNAs allows good matching to be obtained for frequencies all the way down to DC. Resistive-feedback based amplifiers provide wideband matching and flat gain, but suffer from poor NF and large power. In the resistive shunt-feedback amplifier, input resistance is determined by the feedback resistance divided by the loop-gain of the feedback amplifier. Therefore, feedback resistors tend to be of the order of 100 Ω in order to match the low signal source resistance (typically 50 Ω), leading to significant NF degradation. Even with moderate gain, it requires large currents due to its strong dependence for voltage gain on the transconductance of the amplifying transistor. Distributed LNAs, too, consume high currents [14]. The 3-section matching LC network of the LNA in [12] provides input matching over a wide bandwidth because each section is tuned to present a reflection zero at different frequencies. In all the wideband LNAs encountered, a fundamental trade-off that has to be considered is between bandwidth and noise [17].

Impedance matching networks consist of inductors and capacitors, which can be tuned only at a particular frequency, and the LNA is inherently narrow-band. A "multi-band" LNA designed using these blocks thus has to consist of several narrow-band LNAs in parallel. Moreover, there is no possibility of sharing the matching components between different bands. Theoretically, therefore, a *n*-band LNA will occupy *n* times as much chip area as a single-band LNA [16], [31], [33].

The suitability of a wideband LNA to different standards is not merely dependent on its bandwidth. It should be able to provide variable signal gain depending on the necessity. In instances where linearity requirements are strict, a moderate gain is needed because linearity is generally inversely proportional to the gain. When the transceiver's noise figure is more important, the LNA needs to provide high gain to attenuate noise contributions of succeeding stages. The LNA's gain should be reconfigurable so that it can highly amplify weak signals and only moderately amplify stronger ones [38].

Control of the LNA's performance, though increasingly important, is generally neglected. Among the rare instances where it is observed, the easiest method is to add a variable-gain stage at the output [22]. The gain is controlled by varying the bias of this second stage. Sometimes, LNA performance is controlled using the bias of the core amplifier [34]. Besides the gain, the NF and matching depend on the supply. The improvement in the performance comes at the cost of higher consumption. Distributed amplifiers, as mentioned above, are the easiest solution: the higher the number of stages that are turned 'on' by the biasing current, the higher is the gain [8]. In most LNAs the gain provided by the amplifier is only controllable in two steps: peak gain, or zero gain. Such LNAs are equipped with a bypass circuit leading to two modes of operation [29].

3.5 Comparative Analysis

From the presentations above, it can be observed that single-transistor solutions present small chip area, low consumption and low supply voltages. The noise parameters of LNAs remain the same as those of the transistor itself, thus simplifying the noise analyses. Because the input and output matching circuits are dependent on each other, it is difficult to obtain simultaneous match for optimum power transfer and low noise. The circuit contains only one transistor and isolation to reverse signals is very low. This factor becomes all-important when considering the leakage of the mixer signals to the LNA. Broadband matching is difficult due to the capacitive nature of the transistor input.

The popularity of the cascode is explained by various factors. First, the second transistor improves the isolation to the reverse signal. Simultaneous matching of the impedances for optimal noise and power transfer is easier in cascode LNAs because the two impedance matching circuits are independent of one another. The deleterious Miller effect, which limits bandwidth and increases noise in one-transistor amplifiers, is attenuated by the presence of the common-base/gate transistor, which avoids amplification of the base-collector capacitance of the common-emitter transistor. On the flip side, the supply voltage has to be high to bias both the transistors. The minimum supply voltage is thus around 1.4 V. The presence of a second noise contributor increases the noise figure and reduces the output voltage swing.

Having defined the performance that an amplifier must give in order to be a good candidate for low-noise amplifiers in modern wireless systems, we now proceed to describe a new class of LNAs.

4. A New Class of LNAs

Voltage amplification can be realized using two controlled current conveyors as the starting point. The operation and characteristics of the current conveyors have been presented elsewhere and will not be repeated here [39].

4.1 Guiding Principle

Two conveyors, labeled CCCII 1 and CCCII 2, can provide voltage amplification if connected as shown in Fig. 1a. Conveyor CCCII 1 converts the input voltage into a current, the connection of the two conveyors amplifies this current, and conveyor CCCII 2 converts the amplified current into the output voltage.

When voltage V_{IN} is fed at port Y_1, the intrinsic resistance R_{X1} of CCCII 1 converts it into current I_{X1}.

$$I_{X1} = -\frac{V_{IN}}{R_{X1}}. \tag{1}$$

Since CCCII 1 is a current follower between its ports X and Z, I_{X1} is copied to Z_1. Because of the connection of the two, this current I_{Z1} enters port X_2 of CCCII 2. Current $I_{X1} = I_{Z1} = I_{X2}$ is converted to a voltage because of resistance R_{X2}. It appears at the output voltage V_{OUT}.

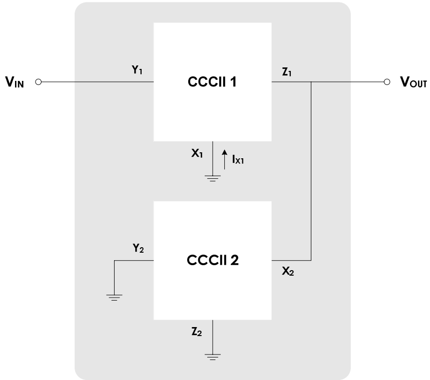
$$V_{OUT} = -R_{X2} \cdot I_{X1} = \frac{R_{X2}}{R_{X1}} \cdot V_{IN}. \tag{2}$$

In conveyors, the intrinsic resistance R_X is inversely proportional to the biasing current I_O. This is the basis of controlled conveyors: the properties of the conveyor (especially its R_X) can be controlled using I_O. In classic translinear loop conveyors, for example, $R_X = V_T/2I_O$ where V_T is the thermal voltage (26 mV at 27°C) [39]. The gain of the amplifier is thus given by

$$A_V = \frac{V_{OUT}}{V_{IN}} = \frac{R_{X2}}{R_{X1}} = \frac{I_{O1}}{I_{O2}} \tag{3}$$

4.2 Circuit Design

The class A current conveyors presented in [40] were chosen for the following reasons. The absence of PNP transistors (whose transition frequency f_T is much lower than that of NPN transistors) allows high bandwidths to be attained, compared to NPN-PNP conveyors. Because of the low number of transistors, noise and distortion are lower. The low number of transistors allows for low supply (as low as ±1.5 V) and reduces the consumption. The gain profiles are stable and flat up to the gigahertz range. Although the linearity is limited by the class of operation, the linearity of the final LNA was sufficient. Therefore, the use of the simple all-NPN class-A conveyors allows for the optimization of the major parameters that define the LNA: gain, bandwidth, linearity, noise and consumption.



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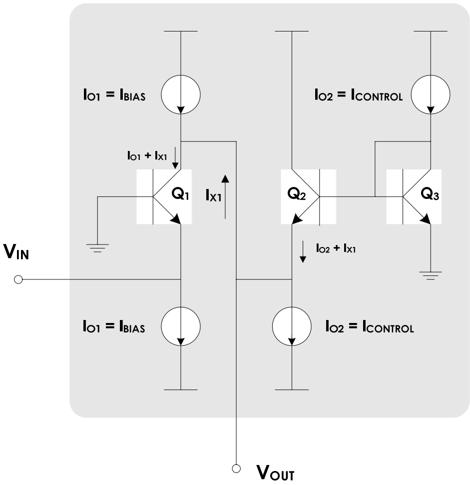

b

Fig. 1. New CCCII-based Low-Noise amplifiers (a) Guiding principle; (b) Final transistor-level diagram.

According to the schema presented, the input signal is fed at port Y whose intrinsic impedance is of the order of some hundred kΩ. Port X, on the other hand, has impedances R_X lower than some hundreds of ohms; R_X can be reduced to 50 Ω for higher values of I_{O1}. Therefore, the input signal is shifted from port Y_1 to X_1. The subsequent changes and optimization of the architecture lead to the basic transistor-level schematic of the LNA shown in Fig. 1b. Biasing currents I_{O1} and I_{O2} are re-named I_{BIAS} and $I_{CONTROL}$ respectively.

On the transistor level, the operation of the LNA can be explained as follows. Input voltage $V_{IN}(t)$ is applied at the emitter of Q_1, around a DC offset equal to the base-emitter voltage of Q_1, $V_{BE,Q1}$. $V_{IN}(t)$ induces an alternating current $i_{X1}(t)$ at port X of Q_1, hereafter referred to as I_{X1}. The collector current of Q_1, $I_{C,Q1}$ is thus the sum of the DC current I_{O1} and $i_{X1}(t)$. Because of the connection between the collector of Q_1 and the emitter of Q_2, the emitter current of Q_2, $I_{E,Q2}$, is the sum of I_{O2} and $i_{X1}(t)$. Since the collector and emitter currents of a transistor can be considered equal, the collector currents of the two transistors are given by:

$$I_{C,Q1} = I_{O1} + I_{X1} = I_{O1}\left[1 + \frac{I_{X1}}{I_{O1}}\right], \tag{4}$$

$$I_{C,Q2} = I_{O2} + I_{X1} = I_{O2}\left[1 + \frac{I_{X1}}{I_{O2}}\right]. \tag{5}$$

Since the base of Q_1 is on ground level, $V_{IN} = -V_{BE1}$.

Now, V_{BE1} can be expressed in terms of the collector current I_{C1} of Q_1 as

$$V_{BE1} = V_T \cdot \log\left[\frac{I_{C1}}{I_{SAT}}\right] = V_T \cdot \log\left[\frac{I_{O1}}{I_{SAT}}\left(1 + \frac{I_{X1}}{I_{O1}}\right)\right] \tag{6}$$

where I_{SAT} is a constant. Given that log(AB) = log$A$ + log$B$ and that log (1+a) ~ a when a<<1, this equation changes to

$$V_{IN} \approx -V_T \cdot \log\left[\frac{I_{O1}}{I_{SAT}}\right] - V_T \cdot \frac{I_{X1}}{I_{O1}}. \tag{7}$$

The first term in this equation corresponds to the constant DC component of V_{BE} of Q_1, and the second term is the alternating part induced by the input.

Therefore, $V_{IN} \approx -V_T \cdot \frac{I_{X1}}{I_{O1}}$.

Applying the same principle to the output voltage,

$$V_{OUT} = V_{E2} = V_{BE3} - V_{BE2}. \tag{8}$$

Expressing the base-emitter voltages in terms of collector currents, and these in turn in terms of biasing current I_{O2} and I_{X2} gives:

$$V_{OUT} = V_T \cdot \log\left[\frac{I_{O2}}{I_{SAT}}\right] - V_T \cdot \log\left[\frac{I_{O2}}{I_{SAT}}\left(1 - \frac{I_{X1}}{I_{O2}}\right)\right]. \tag{9}$$

Simplifying this equation leads to

$$V_{OUT} = -V_T \cdot \frac{I_{X1}}{I_{O2}}. \tag{10}$$

The voltage gain A_V of the LNA is given by

$$A_V = \frac{V_{OUT}}{V_{IN}} = \frac{-V_T \cdot \left[\frac{I_{X1}}{I_{O2}}\right]}{-V_T \cdot \left[\frac{I_{X1}}{I_{O1}}\right]} = \frac{I_{O1}}{I_{O2}}. \tag{11}$$

The noise of the LNA is dominated by the input transistor Q_1; more specifically, its base resistance r_B and collector current I_C. The emitter length was increased to 10 µm to increase I_C. Three transistors were placed in parallel and the base was cut into five parts to reduce r_B.

Equation (11) shows that in its simplest expression, the gain is the ratio of the biasing currents of the two conveyors. The input signal V_{IN} is fed at port X_1 of CCCII 1. The impedances of the two ports of the LNA are required to be 50 Ω. The input impedance Z_{IN} of the LNA is thus simply the intrinsic impedance Z_{X1}. It can be controlled using the biasing current I_{O1}, which is fixed to give $|Z_{X1}| = |Z_{IN}| = 50\ \Omega$. Since the value of I_{O1} is fixed, it will henceforth be called I_{BIAS}. The output impedance Z_{OUT} is a combination of Z_{Z1} of CCCII 1 and Z_{X2} of CCCII 2. Z_{OUT} can be fixed to 50 Ω using the two biasing currents. I_{O1} ($= I_{BIAS}$) is already fixed to give $|Z_{IN}| = 50\ \Omega$. Fixing I_{O2} also will take away the biggest advantage of this LNA: the easy control of its performance. Therefore, I_{O2} is kept free of the impedance constraint, and another way of matching the LNA's output impedance has to be investigated. A new method of matching the output impedance of a RF circuit to a desired value using a current conveyor in the voltage follower mode was used [1]. This makes the output impedance of the LNA independent of its gain.

The gain of the LNA is the ratio of its biasing currents. Current I_{O1} ($= I_{BIAS}$) is fixed by the need for impedance matching of the LNA input. Output matching is obtained using a novel approach. This renders I_{O2} independent of the impedance matching. I_{O2} This current will be used to control the performance of the LNA, and will henceforth be called $I_{CONTROL}$. The inverse proportionality between the gain and $I_{CONTROL}$ presents some notable advantages. Chief among these is the possibility of obtaining high gains for low currents.

Finally, the current sources were replaced by CMOS mirrors. The core of the new LNA contains a very low number of transistors in its signal path (three NPN), and will therefore benefit from low consumption and noise. The matching circuit contains 2 NPN and 2 PNP transistors. It introduces negligible distortion to the signal. Moreover, the LNA's noise figure is dominated by the input transistor of the core amplifier; the addition of the matching circuit engenders a very low deterioration in the NF. The necessity of copying the biasing current into the different branches adds current mirrors consisting of a total of 14 CMOS devices. The complete single-ended LNA architecture is shown in Fig. 2.

The most transistor-laden branch of the LNA consists of 4 transistors between the supply rails. In order for the circuit to function, a ground-referred voltage supply of at least 2.8 V is required. It was found that the new LNA provides good operation for supplies as low as ±1.5 V. Increasing the supply voltage to ±2.5 V was found to greatly improve the performance, especially its bandwidths.

4.3 Fabrication Technology

In 2002, silicon-based devices accounted for more than 98% of sales in the global semiconductor market, owing mainly to their low costs [41]. Silicon has gradually been supplanted by a new composite: silicon-germanium (SiGe) [41]-[44]. SiGe offers a bridge between low-cost, low-power, low-frequency silicon chips and high-cost, high-power, high-frequency chips made from materials such as Gallium-Arsenide (GaAs). In SiGe, peak transition frequencies are obtained for lower collector current and noise figures are reduced up to frequencies of 10 GHz [43]-[45]. SiGe processes also offer easy integration of CMOS devices to create BiCMOS technologies. The advantages of BiCMOS is its lower cost (due to fewer manufacturing steps) and the possibility of mixed-signal integration using one single technology [44], [45].

The LNA circuit was fabricated in the 0.35µm SiGe BiCMOS process from STMicroelectronics. This process is optimized for low-power RF SoC applications, but also enables high performance digital applications. The process proposes a parameterized vertical NPN transistor optimized for 3.6 V operation [46]; it also proposes scaleable vertical PNP. The f_T of the NPN transistors peak at 45 GHz at 3.3 V and that of the PNP devices go upto 5 GHz. The NF of the NPN transistor, at 2 GHz, is 0.8 dB [47]. The technology contains complementary MOS transistors whose channel width and length can be scaled according to choice, subject to the minimum length limit of 0.35 µm. The technology contains 1 poly layer and 5 metal layers.

4.4 Measurement Techniques

Generally, ICs are encapsulated in packages and then soldered on a printed circuit board. The measurements thus carried out are highly dependent on the properties of the cables that link the IC to the apparatus and on the type of packaging itself. Moreover, these are measurements 'at a distance'. Measurements using micro-probes allow performance evaluation directly on the silicon wafer, giving a better idea of the 'intrinsic' performance. The Karl Süss PA200 measurement bench is one such ensemble [48]. The temperature of the thermo-chuck can be regulated, allowing the measurement of the temperature stability of circuits. A Faraday cage offers high immunity to electrical noise as well as light. On-wafer measurements allow the characterization of a circuit's performance as close to a real environment as possible, by minimizing cable parasitics and eliminating packaging faults. Micro-probes are placed on the circuit's pads. The DC micro-probes terminate in fine needles of diameter < 1 µm. For the frequency-domain analyses, single-ended AC probes of the Ground-Signal-Ground (GSG) type are used. Since the signals are of defined with the ground plane as reference, the set-up allows only single-ended characterization of circuits.

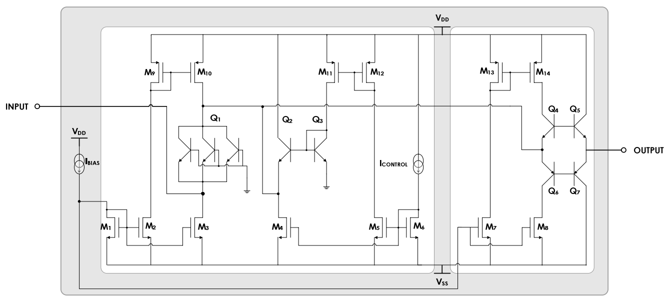

Fig. 2. Complete transistor-level description of a single-ended LNA based on the new principle.

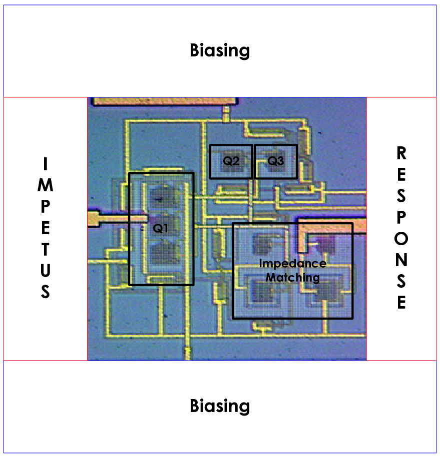

Fig. 3. The Single-Ended LNA.

5. New Single-Ended LNA

5.1 Description of the Circuit

Fig. 3 presents the 50Ω single-ended LNA. The total area occupied by the LNA is 0.022 mm² without the pads (with pads, it is 0.206 mm²). The LNA is biased under a dual voltage supply (nominally, ±1.5 V). Bias current I_{BIAS} sets the values of both Z_{IN} and Z_{OUT}. $I_{CONTROL}$ is the means of controlling the gain of the LNA. Transistor Q_1, at whose emitter the input is applied, is the major contributor of the noise. The output is matched using the new impedance matching circuit.

5.2 Measured Performance

Gains between 0 dB and 14 dB are obtained for $I_{CONTROL}$ varying between 50 µA and 550 µA. The LNA consumes between 3 and 4.5 mA for the entire range of $I_{CONTROL}$. These values are similar to those obtained from simulations. Fig. 4 depicts the gain and the bandwidth of the single-ended LNA. For gains higher than about 10 dB, the bandwidth is lower than 0.9 GHz, but it improves at moderate and low gains. The gain control of the LNA is smooth, and intermediate gains can be obtained by fine-tuning $I_{CONTROL}$. Peak bandwidths of 3.5 GHz were attained.

The other three S parameters are shown in Fig. 5 below. The input impedance is excellently matched over a multi-GHz band: S_{11} is lower than -10 dB upto 4 GHz, for all values of $I_{CONTROL}$. Below 1 GHz, S_{11} < -15 dB and upto 2 GHz, S_{11} < -13 dB. Output matching is excellent upto 1.8 GHz. The strength of the reverse signal is extremely low: upto 5 GHz, S_{12} is lower than -26 dB for all values of the LNA gain.

The gain is dependent on $I_{CONTROL}$. This same current also changes the operating point of the transistors, notably their r_B and I_C, which in turn change the noise figure. The simulated NF is lower for higher gains (at 15 dB of gain, the NF is 1 dB, it goes upto 6 dB for 0 dB of gain). Therefore, in terms of the trade-off between gain and noise figure, the LNA works best at moderate and high gains (Fig. 6).

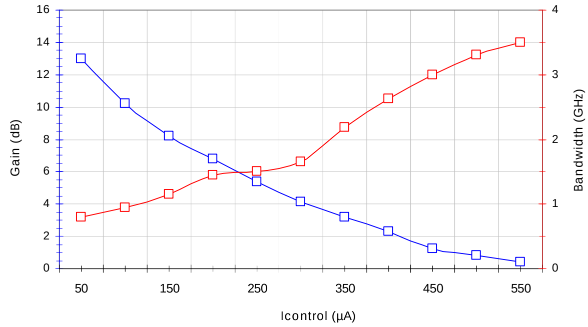

Fig. 4. Gain and bandwidth of the single-ended LNA at V_{DC} = ±1.5 V and I_{BIAS} = 450 µA.

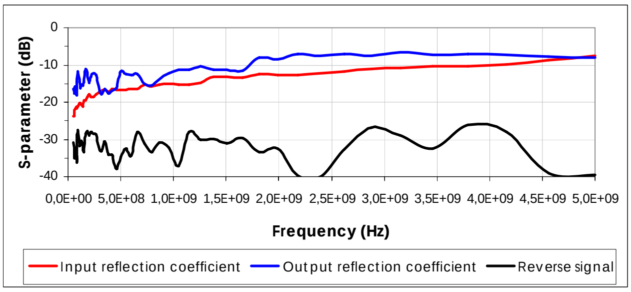

Fig. 5. S-parameters of the single-ended LNA, for gain = 6dB; at V_{DC} = ±1.5 V and I_{BIAS} = 450 µA.

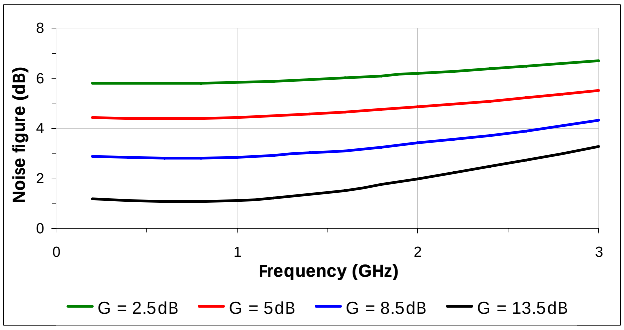

Fig. 6. Noise figure profiles for the single-ended LNA.

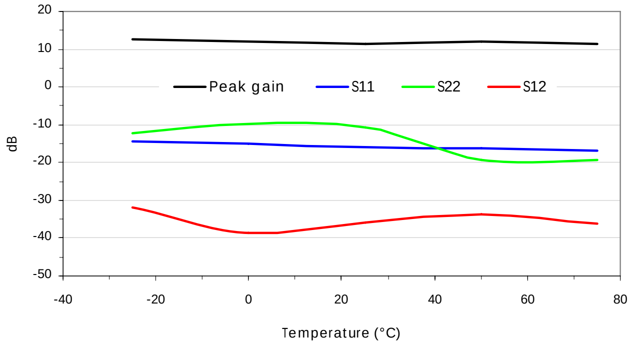

Fig. 7. S-parameters of the single-ended LNA, versus temperature, for gain = 10 dB; at V_{DC} = ±1.5 V.

For $I_{CONTROL}$ = 200 µA, and at input signal frequency of 1 GHz, the input-referred P_{1dB} was found to be -12.5 dBm. For the third-order intermodulation product, two tones of -30 dBm intensity were applied at 1 GHz and 1.02 GHz. At the output the 3rd-order terms 30.28 dBm, 5th-order terms 48 dBm, and 7th-order terms 72 dBm lower than the fundamental were observed. The input-referred third-order intermodulation point was determined to be -12.04 dBm.

The temperature of the thermo-chuck on which the wafer is mounted was changed from -25°C to +75°C, and the LNA's performance was measured to determine its temperature stability. Fig. 10 depicts the temperature stability of the gain, impedance matching and reverse isolation. A representative case is taken: LNA gain of 10 dB, at 1 GHz. The impedance matching at both the input and the output remains good (S_{11} and S_{22} are both lower than -10 dB). The reverse signal isolation remains better than -30 dB. The gain of the LNA shows variations of ±0.6 dB around the ambient temperature value of 12 dB.

5.3 Comparison with Existent LNAs

The relevance of the new LNA for present-day wireless transceivers can be determined on comparison with solutions that exist in published literature. Tab. 2 presents some recent single-ended LNAs, along with the new conveyor-based solution. This table contains LNAs that we deemed most representative in terms of applications (standards from CDMA to UWB are covered) and in terms of performances. The performance of the new LNA given is that obtained at gains of 3 dB and 13 dB, the two extremes of the gain control range.

Existent low-noise amplifiers inevitably make use of passive elements, thus increasing their area, and often ruling out single-chip solutions (the passives often have to be placed off-chip).

The new single-ended LNA is an all-active circuit, and its size is 40-50 times smaller than most other LNAs - and at least four times smaller than the smallest LNA observed in existent literature [17].

The consumption of existent LNAs varies widely, depending on the gain of the LNA, but is almost always greater than 5 mA (barring the 2.5 mA consumption of the LNA in [10]). In contrast, the new LNA consumes less than 4.5 mA for the entire range of gains it provides. This figure is better than the best consumption noted in existent LNAs.

The impedance matching circuitry is the most area-consuming part of most LNAs. Successful matching is achieved in very narrow bands (over which the passive network resonates). The new LNA attains good matching for all frequencies between 0 and 4 GHz. Moreover, matching is independent of the gain of the LNA, contrarily to, for example, the LNA in [34].

Each communication standard has its specific exigencies with respect to the linearity. The IP_{1dB} of the new LNA is much higher than the GPS LNA in [24], comparable to the PCS1900 LNA in [21] and the WCDMA LNA in [11]), and only slightly worse than the highest observed IP_{1dB} [10].

Gain control is a rare feature in existent low-noise amplifiers. When it is included, the gain control range is rather limited and power consumption increases with the gain (for example, the LNA in [34] provides gains ranging from 10 to 14 dB, with power dissipations of 5 mW and 15 mW respectively). By contrast, the gain of the new single-ended LNA can be varied between 0 and 13 dB. The inverse relation between the gain and the control current means that best gains are obtained at lowest power dissipation.

Reference; Year	**[15]; 2006**	**[24]; 2002**	**[21]; 2001**	**[17]; 2004**	**[14]; 2005**	**This work**	
Frequency	0.88GHz	1.23GHz	1.9GHz	0 – 2GHz	3 – 5GHz	**0 – 2GHz**	
Applications	CDMA	GPS	PCS1900	Wideband	UWB	**Wideband**	
Technology	.25µmCMOS	.25µmCMOS	.5µmCMOS	.25µmCMOS	0.18µmCMOS	**0.35µmBiCMOS**	
Passives	8	8	3	8	9	**0**	
Area	- n.a. -	0.66mm²	1.3mm²	0.08mm²	0.9mm²	**0.022mm²**	
Peak gain	16.2dB	20dB	15dB	13.7dB	9.8dB	**0dB**	**10dB**
Bandwidth : f_L, f_H	- n.a. -	1.0-1.4GHz	1.7-2.1GHz	0-1.6GHz	2.0-4.6GHz	**0-3.5GHz**	**0-0.95GHz**
Consumption	12mA	6mA	25mA	14mA	- n.a. -	**4.2mA**	**3.2mA**
Dissipation	31.2mW	9mW	25mW	35mW	12.6mW	**12.6mW**	**9.6mW**
S_{11}; S_{22}	-10dB; -10dB	-11dB, -11dB	-22dB, -10dB	< -10dB, < -8dB	< -9dB, < -10dB	**< -13dB, < -10dB**	
S_{12}	- n.a. -	< -31dB	- n.a. -	< -36dB	< -20dB	**< -28dB**	
IP_{1dB}	- n.a. -	-24dBm	-11dBm	- n.a. -	- n.a. -	**-12.5dBm**	
Noise figure	1.2dB	0.8dB	1.8dB	2.4dB	2.3dB	**6.8dB***	**1dB***

Tab. 1. Comparison between the new single-ended LNA and some other recent solutions.

6. Conclusions

The aim of this article has been to update the state of the art in low-noise amplifiers for wireless communications receivers. An exhaustive review of existent LNA solutions led to the conclusion that today's LNAs are based on three distinct topologies: single-transistor, cascode and two-stage. Cascode-based LNAs are the most widespread. Most LNAs are narrow-band structures. Wideband LNAs provide bandwidths of the order of gigahertz, but at the expense of increased consumption and noise, and moderate gains. It was also observed that gain control in low-noise amplifiers is a rare phenomenon, even though it is deemed indispensable in today's mobile environments.

The ultimate aim was to design a LNA that exhibits the following properties: performance (gain, noise, consumption, linearity, etc.); small size (low number of passive elements); high bandwidths (enabling the new LNA to replace several narrow-band in multi-standard receivers); and easy gain control over wide ranges (without overly effecting the other parameters of the LNA).

A novel low-noise amplifier was then developed. The guiding principle is the connection of two second-generation current controlled conveyors to provide signal amplification. A new category of LNAs was thus developed. To verify operation in a real environment, it was fabricated in a f_T = 45 GHz 0.35µm SiGe BiCMOS technology. Optimization of the circuit design enabled final configurations that use only three NPN transistors in its signal chain.

The absence of passives results in very small form factors (0.02 mm²). This is the smallest LNA noted so far. Gain control over wide ranges (0 – 15 dB) is obtained by simply varying the bias current. This is the widest range of gain control encountered for LNAs. The LNA presents wideband matching frequencies extending from 0 to over 4 GHz. Since the highest gains are obtained at lowest control currents, the LNA dissipates the lowest power when providing moderate to high gains. The consumption is lower than 4.5 mA for the entire range of gains between 0 and 20 dB. The inverse proportionality between the gain and control current translates to another significant advantage: best noise performance at high gains. The noise figure varies between 1 dB at 20 dB of gain, to about 4 dB at gains of 5 dB. The LNA has input-referred P_{1dB} comparable to the best linearity performances.

The performance is stable to variations in temperatures from -25°C to +75°C. Finally, the performance of the circuit is reproducible.

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