Journal of Engineering and Applied Sciences 8 (1): 21-28, 2013
ISSN: 1816-949X

Low Noise Amplifiers in RFID Systems

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Abstract: The efficiency of Radio Frequency Identification (RFID) readers and tags largely depend on the performance of Low Noise Amplifier (LNA). This study presents different types of LNA used in RFID tags. LNAs are mainly separated into two groups. The 1st group is the inductive LNA and the 2nd group is inductor-less LNA. Each group is discussed in detail. In the LNA design, there are very important factors that play vital role in LNA performance such as voltage gain, Noise Figure (NF), power consumption, chip size and cost. This study covers all different designs and the advantages and disadvantages of each design. The study presents an idea about the effective area and suitable application for various designs with some solutions.

Key words: CMOS, inductor, LNA, noise figure, RFID, chip size, cost

INTRODUCTION

RFID is a very familiar and emerging technology which is being used everywhere now-a-days (Akter *et al*., 2008a, b; Reaz *et al*., 2003, 2005, 2007a, b; Marufuzzaman *et al*., 2010; Cheng *et al*., 2012). RFID is the utilization of radio waves to transfer data between a reader and a tag attached to an object for the purpose of identification and tracking. The efficiency of RFID readers and tags largely depend on the performance of LNA which has many factors controlling this performance (Reaz *et al*., 2006; Reaz and Wei, 2004; Mohd-Yasin *et al*., 2004; Mogaki *et al*., 2007). The main factors in LNA design are voltage gain, NF, power consumption, size and cost, linearity and bandwidth.

Different LNA designs are presented in this study. Firstly, the inductive LNA is presented which is divided into two groups according to it is feedback connection. There are many techniques which are discussed to improve those designs. Secondly, inductor-less LNA is presented. Every group of LNA designs in this study is compatible with specific application. The advantages and disadvantages of each group are highlighted in details.

CATEGORIES OF LNA

Inductive LNA: This type of LNA contains multi-stage amplifier with combinations of inductors, capacitors and resistors. These components have a basic role to improve the input impedance and to obtain wide bandwidth. The inductors and capacitors are implemented using off chip components or on-chip components, such as spiral inductors. But, they take large chip area and the implementation cost is also high (Weng *et al*., 2010). Many researchers proposed various methods to solve the problem which is explained in the subsequent paragraphs.

LNA without feedback: This type of LNA does not have any connection between the input and output. Most of the designs use Common Gate (CG) amplifier at the input stage as it provides better input matching, lower NF and more reverse isolation which is preferable in LNA design. A typical LNA is shown in the Fig. 1. Mainly, the input is connected to CG amplifier and then Common Source (CS) amplifier is used to get high voltage and finally the output is taken from the output of CD amplifier.

Chip size and implementation cost: As discussed before, the On Chip inductors need large area and high cost. Two methods are used to reduce these issues. LC network is one of the methods to overcome this problem. In Fig. 2, an LC network and the equivalent circuit is shown. The large space occupying inductor is replaced by a small LC circuit (Rad *et al*., 2010). L_g and R_g are evaluated by Eq. 1 and 2. The patterned ground shield as shown in Fig. 3 is used to minimize the cost as well as area. Additionally, this also solves the coupling and EM problem:

$$L_g \approx \frac{1}{1-LC\omega^2} \quad (1)$$

$$R_g \approx \frac{R_{g1}}{(1-LC\omega^2)^2} \quad (2)$$

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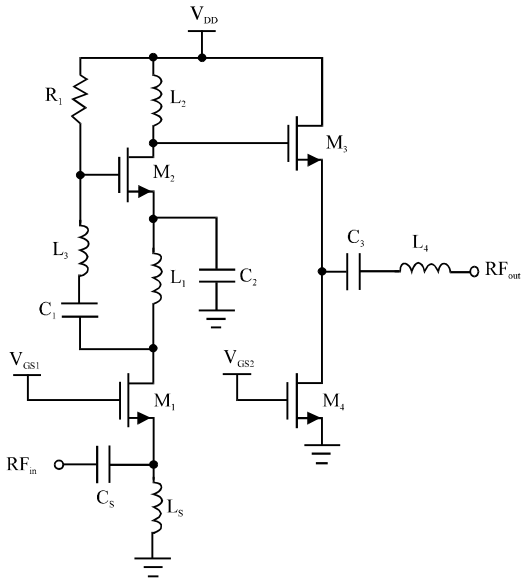

Fig. 1: Typical LNA using CG configuration (Weng *et al*., 2010)

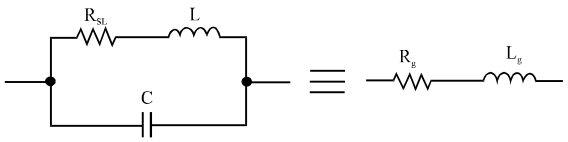

Fig. 2: LC network circuit and equivalent circuit (Rad *et al*., 2010)

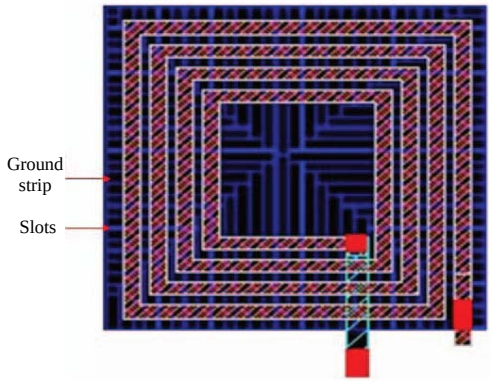

Fig. 3: The patterned ground shield (Liu and Wang, 2011)

Power consumption and reliability: The power consumption and reliability are important design issues, especially for portable devices like RFID tags. Dual Path Noise Cancelling (DPNC) LNA is used to resolve this issue (Hsu *et al*., 2010). Figure 4 shows the conventional noise canceling LNA which cancel thermal noise from CG but it cannot cancel the noise from CS. So, increasing the transconductance (g_{m2}) of CS can solve this problem.

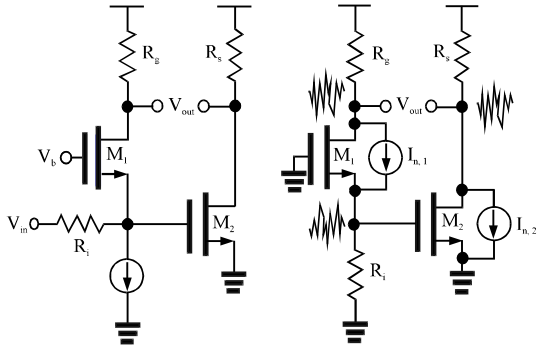

Fig. 4: Conventional noise canceling LNA (Hsu *et al*., 2010)

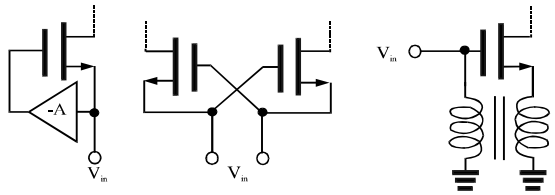

Fig. 5: g_m improvement techniques (Hsu *et al*., 2010)

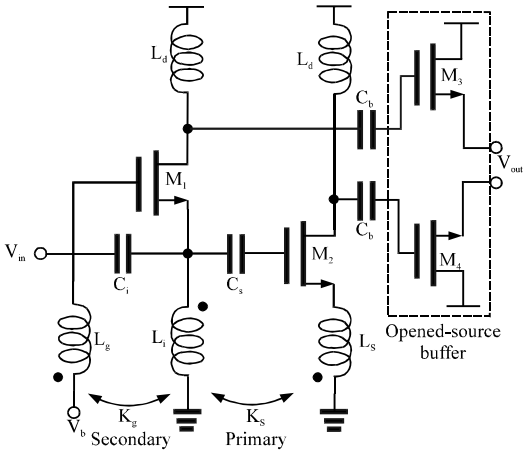

Fig. 6: Double noise canceling LNA (Hsu *et al*., 2010)

There are three methods to improve the g_{m2}. These are active, cross and magnetic coupled as shown in Fig. 5 (Hsu *et al*., 2010). Active coupled (dual feedback) has high gain and low NF and the chip consumes 10.8 mW power (Ye *et al*., 2011). On the other hand, the magnetic coupled design consumes only 1.2 mW power. The cross coupled method is insufficient because the ratio is fixed to 2. So the magnetic coupled is used because the ratio of improvement in g_{m2} equal to transformer turn-ratio.

By adding these modules to original circuit and altering the open source buffer, the voltage gain is

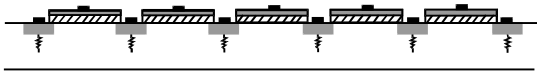

Fig. 7: Number offinger topology (Roh *et al*., 2008)

increased up to 22 dB and the NF to 3.7 dB. It consumes only 1.2 mW power and reliability is high. The modified circuit is shown in Fig. 6.

High linearity: Common gate amplifier has a good reverse isolation. Body effect is important factor in IC design as the parasitic resistance between sources to bulk of MOSFET changes the threshold voltage. One solution to decrease this effect is the count finger as shown in Fig. 7.

LNA WITH FEEDBACK

Feedback is a common technique that is applied in the design of wideband amplifiers to obtain the input matching. In the feedback LNA, there are connection between the input and output. The connection is a resistor and gate inductor at the input. At times, a source follower is altered as a feedback buffer also. There are few feedback techniques which are discussed in this study.

Common source LNA with feedback technique: Achieving the noise matching in the input termination to obtain the minimum noise factor is the main goal in LNA design. In order to achieve a good input matching, high gain and wideband performance, LNA with resistive shunt feedback topology has been introduced and developed (Chang and Hsu, 2010; Chang *et al*., 2008; Sasilatha and Raja, 2011; Ansari and Plett, 2010; Kim *et al*., 2011; Perumana *et al*., 2008). A feedback resistor needs to be used to extend the bandwidth. With the large input transconductance, LNA design using resistive feedback can achieve very wide bandwidth and high gain which is >10 dB at the same time. It also reduces generation of NF <3 dB under a large bias current.

Designing ultra wideband LNA with resistive feedback: Resistive feedback LNA can achieve wideband from 0-22 GHz (Okushima *et al*., 2009). It has also low power consumption and high gain. This technique takes into the consideration since negative feedback had a tendency to minimize the input impedance of amplifier as well as extend the bandwidth with reduction of trade-off gain. As comparison to the other techniques, a smaller chip area can be achieved by resistive feedback LNAs configuration since there are no or less inductors being introduced and utilized. As a result, it is able to produce a reasonable high voltage gain. To enhance the performance of LNAs in terms of bandwidth extension

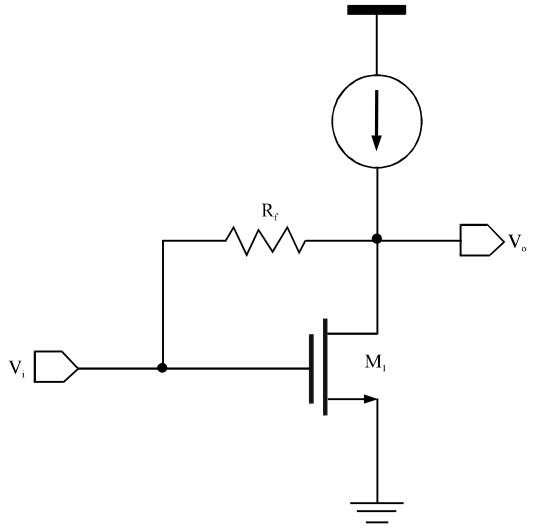

Fig. 8: CS amplifier with resistive feedback (Chang and Hsu, 2010)

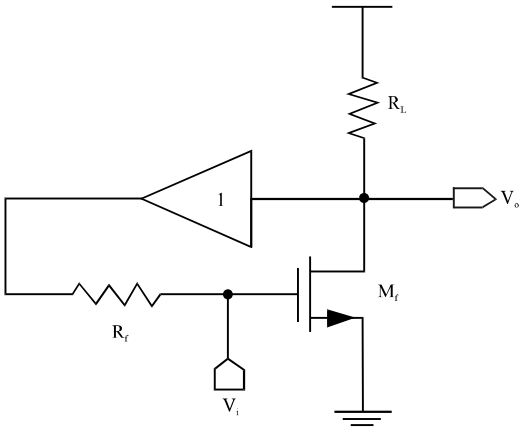

Fig. 9: Resistive feedback amplifier with an ideal voltage buffer (Chang and Hsu, 2010)

and input matching, numerous techniques were proposed and developed based on the resistive feedback approach. The basic schematic of the common source amplifier with a resistive feedback is shown in Fig. 8.

The CS amplifier is incapable to achieve a good input matching and low NF. Regarding this limitation, the voltage buffer has been introduced and used with feedback resistor to improve input matching and NF. The modified design is shown in Fig. 9.

Theoretically in this topology, the increment of the transistor transconductance g_m results the reduction of the NF. With an appropriately designed feedback resistor (R_f) and load resistor (R_L), the input matching can be enhanced. Voltage buffer implementation via a source follower is widely used as shown in Fig. 10.

The resistive feedback design through a source follower can be improved by inserting a gate inductor peaking at the input of LNA which increases the bandwidth and minimizes the NF at the same time. However, the large value of the inductance added into a gate inductor will increase the chip area. As reported by Chang and Hsu (2010) and Chang *et al.* (2008), a smaller value of gate inductor, L_g has been used to extend the bandwidth whereby the gate inductor was placed inside the feedback loop of the input transistor. This design shown in the Fig. 11 with a small gate inductor (0.3~0.4 nH) were selected and utilized to create LC resonant frequency in the range of 14-16 GHz. By using this technique and as comparison to the circuit without inductor, the bandwidth was increased from 11.5 GHz (without any inductor) to 14.2 Ghz which is about 23% enhancement. Moreover, the NF was reduced by 0.94 dB at 10.6 Ghz frequency. As discussed by Chang *et al.* (2008), 0.3 nH of gate inductor (L_g) is capable to boosts the amplifier bandwidth by approximately 40%. The voltage gain under the input impedance matched condition is derived as Eq. 3 $(1-\omega^2 L_g C_{gs1})$. Since, decrease with frequency, the gain reduction due to the pole can be compensated. Thus, the bandwidth is enhanced:

$$\begin{aligned} A_V &\approx -\frac{G_{m1}R_L}{1+j\omega R_L C_L} \\ &= -\frac{\left[\frac{g_{m1}}{1-\omega^2 L_g C_{gs1}}\right]R_L}{1+j\omega R_L C_L} \\ &= -\frac{g_{m1}R_L}{(1-\omega^2 L_g C_{gs1})(1-j\omega R_L C_L)} \end{aligned} \quad (3)$$

On the other hand, the reduction of the amplifier gain caused by the poles can be resolved by increasing amplifier high frequency gain or minimizing the feedback impedance at higher frequencies. As reported by Chang *et al.* (2008), it is not practical to increase high frequency gain. Thus, reducing the feedback impedance at higher frequencies is more relevant solution by adding a capacitor C_f in parallel with resistor R_f. As a result, the input matching can be maintained or enhanced for a wide range of frequencies. Figure 12 shows the small signal equivalent circuit configuration by modifying and adding capacitors with circuit of Fig. 11 to evaluate the performance of input or output matching.

To further enhance the amplifier bandwidth, the neutralization capacitors have been introduced to the circuit. These capacitors are beneficial as it is able to cancel out the gate to drain capacitance at the input

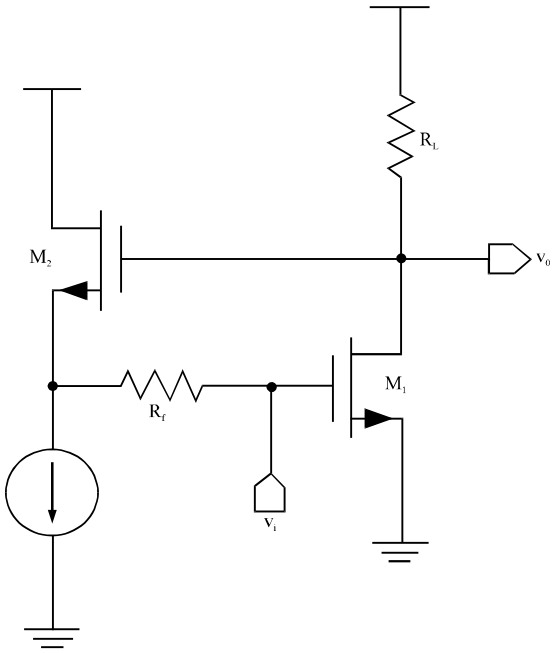

Fig. 10: Source follower buffer in the resistive feedback amplifier configuration (Chang and Hsu, 2010)

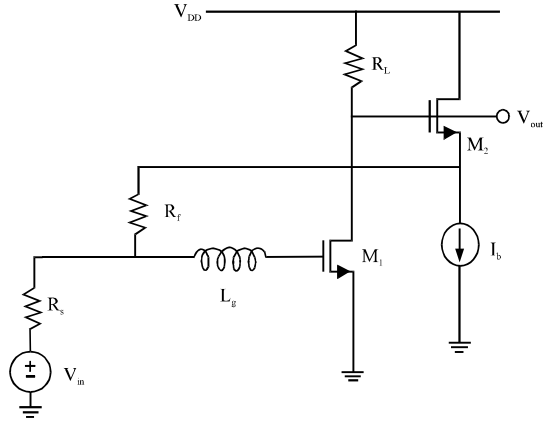

Fig. 11: Schematic of a resistive feedback amplifier with a peaking inductor (Chang *et al.*, 2008)

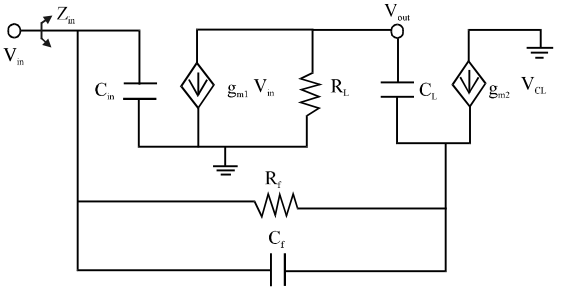

Fig. 12: Small signal equivalent circuit for schematic in Fig. 11 (Chang *et al.*, 2008)

transistor by providing equivalent negative capacitances. Figure 13 shows the circuit of the compact ultra wide band LNA that has been proposed by Chang and Hsu (2010). The design consists of a feedback buffer, a feedback resistor and a gate peaking inductor in the feedback loop of CS amplifier with a current reuse input stage and a source follower for the output buffer. Cascade stage is being used in LNA design to improve the reverse isolation while the current reuse technique is useful to enhance the input transconductance to minimize the power consumption.

The increment in the gate inductor improves the gain and the bandwidth. But, a large gate inductor (>1 nH) can lead to over peaking of gain and can affect circuit stability. Table 1 shows the comparison with the others literatures. Based on this study, resistive feedback LNA with gate inductor peaking is able to achieve a better performance of gain, NF, low power consumption, extend the bandwidth as well as small chip area. Unfortunately, the performance was degraded when the LNA was operated in the high frequency band due to the parasitic capacitances.

Inductor-less LNA: In inductor-less LNA, passive inductor is replaced by active inductor which is mainly combination from one or more of NMOS transistor. The aim of using active inductor is to overcome disadvantages of passive inductor which reduces the size and implementation cost. The area of active inductor is independent on the inductance (Yang *et al*., 2009).

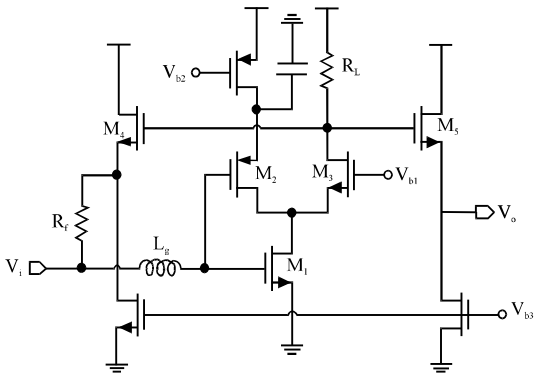

Fig. 13: Circuit schematic of compact UWB LNA(Chang and Hsu, 2010)

Active inductor: An active inductor is shown in Fig. 14. In Fig. 14a, the quality factor inductance and frequency is calculated as the Eq. 4-6 also the Q is high enough as it mainly depends on R_F:

$$L \approx \frac{C_{gs3}(1+R_{fgds4})}{g_{m4}g_{m3}} \tag{4}$$

$$Q \approx \sqrt{\frac{g_{m4}g_{m3}C_{gs3}\times(1+R_{fgds4})}{g_{ds4}{}^2 C_{gs4}}} \tag{5}$$

$$\omega \approx \sqrt{\frac{g_{m4}g_{m3}}{C_{gs4}C_{gs3}(1+R_{fgds4})}} \tag{6}$$

A common-gate amplifier is used with active inductor to obtain a better input impedance matching (Li and Zhang, 2007). In the Fig. 14b, the small signal equivalent circuit is shown and the equivalent impedance equation is given as:

$$Z_{in} = \frac{sR(C_{gs}+C_{gd})+1}{(g_m+sC_{gs})(sR_bC_{gd}+1)} \tag{7}$$

Inductor-less LNA techniques

Noise cancelling technique: In noise cancelling technique, the active inductor is connected with noise

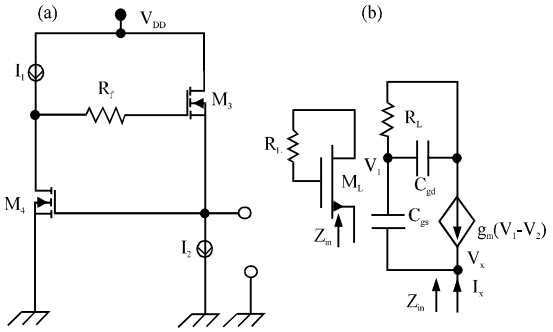

Fig. 14: Active inductor circuits (Yang *et al*., 2009)

Table 1: The measurement results from the past researches in UWB LNA

Researchers	CMOS (μm)	Freq. (GHz)	S_{21} (dB)	NF (dB)	IIP3 (dBm)	ESD	Power (mW)	VDD (V)	Active area (mm^2)
Chang and Hsu (2010)	0.13	3.1-10.6	11.1-12.4	2.7-3.7	-3.80	No	14.4	1.8	0.0310
Chang *et al*. (2008)	0.09	0.2-9	10	4.2 min	-8.00	Yes	20.0	1.2	0.0660
	0.09	0.2-3.2	15.5	1.76 min	-9.00	Yes	25.0	1.2	0.1340
Sasilatha and Raja (2011)	0.12	2.4	20	3.9	-2.88	No	2.0	1.0	0.0184
Anasari and Calvin (2010)	0.13	3.1-10.6	6-7	6.3	-	Yes	5.2	1.2	0.7000
Kim *et al*. (2011)	0.13	0.81-5.7	11.7	2.58-5.11	1.60	No	12.0	1.2	0.6300
Yang *et al*. (2009)	0.09	0.5-7	22	2.3-2.9	-8.80	No	12.0	1.8	0.0120
	0.09	4-8	24.4	2-2.4	-2.60	No	9.2	1.2	0.0220
Okushima *et al*. (2009)	0.09	0-22.1	10.7	4.3	-2.67	No	8.4	1.2	0.0170

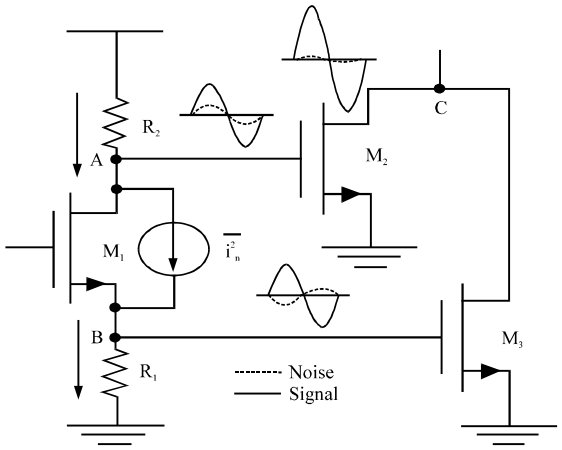

Fig. 15: LNA by using noise cancelling technique (Gao *et al*., 2009)

cancelling circuit. In the noise cancelling technique, the NF will be very low and the original amplified input signal is divided in tow direction by feedback resistance between source and drain. With this technique, the input signal is still same but the noise is out of phase. M2 and M3 convert the voltages to currents and it added at node c so the noise will cancel each other and the original signal is amplified (Gao *et al*., 2009). The noise cancelling technique is shown in Fig. 15.

Resistive feedback technique: In some application, the LNA must have high linearity and wide bandwidth. It is obtained by increasing power consumption or by altering passive components such as inductors (Gao *et al*., 2009). But, the resistive feedback circuit is used to get the same aim and also the voltage is controlled. But, it consumes high power as it has many components.

DISCUSSION

Table 2 shows the advantage and disadvantage comparison between the CS LNA and the CG LNA. A resistive feedback CS LNA with gate inductor by Chang *et al*. (2008), Sasilatha and Raja (2011), Ansari and Plett (2010) has better performance of gain and NF. Unfortunately, the performance degrades when the LNA is operated in the high frequency band. In contrast, ultra wideband common Gate LNA is used instead of ultra wide band common source LNA for few reasons. Firstly, the design used by Fan *et al*. (2005) has a high linearity relative to common source wide band circuit and decreases the power consumption. In contrast, this design has large chip area as it many inductors are used to design it.

Table 2: Comparison between CS LNA and CG LNA

Parameters	CS LNA	CG LNA
NF	+	-
Effective gm	+	-
Parasitic sensitivity	-	+
Input matching	-	+
DC power	-	+
Reverse isolation	-	+

+ = Advantages; - = Disadvantages

Secondly, common gate amplifier is used to get better input impedance matching (Blaakmeer *et al*., 2005). However, this circuit uses common source amplifier which consumes more power. Thirdly, a differential ultra wide band is presented to decrease the NF but this circuit increases the quality factor and causes mismatching as by Shekhar *et al*. (2006). Finally, a single stage common gate ultra wideband is presented by Zhang *et al*. (2009) to get high linearity and also to achieve low power consumption and good input matching.

All of the above designs use inductor which increases the chip area and the implementation cost. However, inductor-less LNA has very small chip size, low cost, high voltage gain and low NF. But, the downside is the power consumption. Finally as mentioned in the discussion, every design has advantages and disadvantages but some of them have advantages more than other and fewer disadvantages than other. However, each design is effective for particular application.

CONCLUSION

In this study, different LNA designs are discussed. It is divided to inductive LNA and inductor-less LNA. In the inductive LNA, there are two designs. Firstly, CSLNA is presented which has high voltage and low NF. Secondly, CG LNA provides better input matching, good reverse isolation and low power consumption. However, in the inductive LNA, the chip size and cost issue appears. The inductor-less LNA overcomes the chip size and cost issue as it does not use inductors. But, the voltage gain is not high enough. Finally, the requirements and the applications decide the preferable design as the disadvantages in one design is important for an specific application but neglected in other applications.

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