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Mixed Linearity Improvement Techniques for Ultra-wideband Low Noise Amplifier

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ABSTRACT

We present the linearization of an ultra-wideband low noise amplifier (UWB-LNA) operating from 2GHz to 11GHz through combining two linearization methods. The used linearization techniques are the combination of post-distortion cancellation and derivative-superposition linearization methods. The linearized UWB-LNA shows an improved linearity (IIP3) of +12dBm, a minimum noise figure ($NF_{min.}$) of 3.6dB, input and output insertion losses (S_{11} and S_{22}) below -9dB over the entire working bandwidth, midband gain of 6dB at 5.8GHz, and overall circuit power consumption of 24mW supplied from a 1.5V voltage source. Both UWB-LNA and linearized UWB-LNA designs are verified and simulated with ADS2016.01 software using BSIM3v3 TSMC 180nm CMOS model files. In addition, the linearized UWB-LNA performance is compared with other recent state-of-the-art LNAs.

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1. INTRODUCTION

The first stage of any RF front-end receiver system is the LNA. The required power sensitivity of the LNA differs from application to another. An important design criterion the LNA is to achieve high linearity to be able to distinguish between the desired RF application signal and the interferers signals that occupy the transmission spectra. The vast majority of military, civilian, and commercial applications utilize UWB standard for its high speed and low power benefits. However, the increasing number of such applications requires the linearity of the LNA to be improved to the level at which the desired signal and the interferers can be distinguished. A literature review for previous LNA designs is presented hereafter to clarify the goal of this paper.

A narrow band 5.8GHz low noise amplifier was designed and verified using ADS software for the IEEE802.16 standard. Undoubtedly, the super HEMT FET Technology consumes large power compared to CMOS technology. Therefore, we choose the CMOS technology for our proposed work. However, the authors of the narrow band 5.8GHz LNA design did not mention the total power consumption of their proposed design. In addition, the 5GHz band became increasingly busy with many applications that may interfere with each other, such as, UWB standard, WiMAX standard, and IEEE802.11a standard. Consequently, there is a rising need that the LNA linearity (IIP3) acquires high values. The IIP3 design criteria for the 5.8GHz LNA had not been considered in the aforementioned paper [1]. Another study of the common gate ultra-wideband low noise amplifier, which used the current-reuse technique, provided low power consumption, high noise figure, and very low linearity of -11.5dBm. Nevertheless, such low linearity is problematic when too many applications reserved the working band [2].

In a prior study of the g_m boosted common gate UWB-LNA, an IIP3 of -6.1dBm and bandwidth of 3.1GHz to 4.8GHz was achieved. However, this band did not serve well the UWB standard because the UWB standard should pass all the frequencies from 3.1GHz to 10.6GHz. In addition, the low IIP3 value of -6.1dBm is considered an issue when many applications utilize the channel [3]. A more recent study of the new LNA topology architecture using inductive drain feedback technique for wireless application showed very good gain and noise performances. However, the operating frequency was busy with other applications. Therefore, the linearity of the proposed structure had to be studied and improved. Other issues considering power consumption and bandwidth had not been studied well [4].

In another study of high gain pHEMT 5.8GHz LNA, there was a very good gain. However, the drawbacks of the study were: the use of an external network for the input matching in the circuit, the lack of power consumption measurement, and the neglecting of the linearity measurement for the circuit in this busy RF channel [5]. A subsequent study of the ultra-low power wideband LNA achieved an IIP3 of -10dBm, high noise figure of 4.9dB, and a bandwidth of 0.1GHz to 2.2GHz [6]. Although the LNA's design operated from 0.6GHz to 4.2GHz was shown to be suitable for ultra-low power applications, the designed bandwidth was already reserved by too many applications. As a result, the achieved linearity of -10dBm limited the efficient use of the receiver [7].

The goal of our work is to achieve better performance for the UWB-LNA, specifically, in terms of linearity (IIP3), through mixing different linearization techniques to obtain more IIP3 improvement. Consequently, the entire receiver's RF-front will be sensitive to the desired signal and more immune to unwanted interferers. In our work, we use the distortion cancellation circuit described in [8] to linearize the UWB-LNA suggested in [9]. In addition, we combine the derivative-superposition linearization technique for more IIP3 improvement for the proposed UWB-LNA circuit. Although both linearization techniques were used previously to linearize narrow band LNAs, our work combines the two-linearization methods to show the high enhancement of linearity for an ultra-wideband LNA.

2. RESEARCH METHOD

The proposed UWB-LNA is shown in Figure 1. The common gate stage (Q_1) is utilized to achieve input return losses below -10dB by controlling the transistor biasing and sizing, which are selected to be 2.7mA and width of 144μm, respectively. In addition, C_s and L_s resonate at the center of the entire band providing more degree of freedom to control the insertion losses. L_s is optimized to 8.831nH and C_s is chosen to be 10pF, which also acts as a DC coupling capacitor. Both L_s and C_s provide sufficient input return losses during the entire bandwidth.

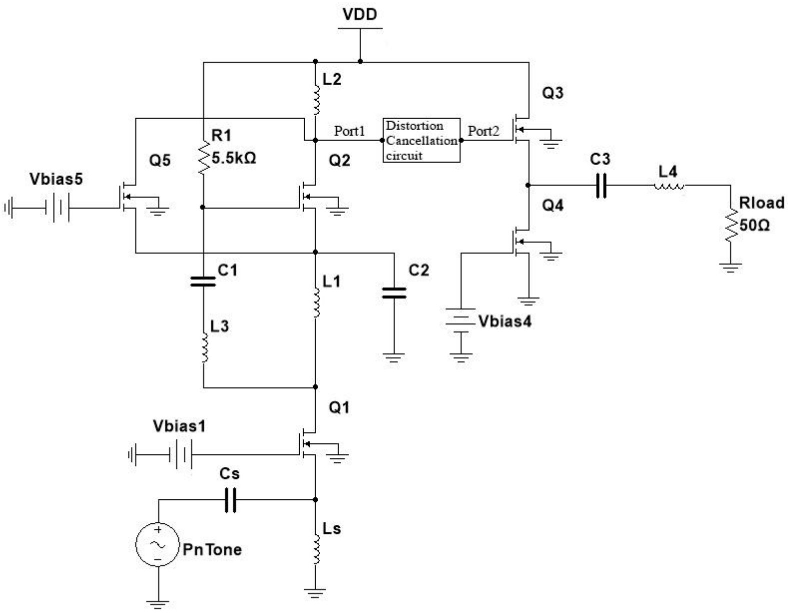


Figure 1. Proposed UWB-LNA

The inter-stage resonating circuit consists of L_1, L_3, C_1, and the parasitic capacitances at the drain of Q_1, which all resonate at the designed f_{low} [9].

$$f_{low} = \frac{1}{2\pi}\sqrt{\frac{1}{(L_1 + L_3)C_1}} \tag{1}$$

The L_2 inductor and the parasitic capacitances at the drain of Q_2 determine the upper frequency of the bandwidth. The L_2 inductor is chosen to resonate with Q_2 drain parasitic capacitor at the desired upper frequency [9].

$$f_{high} = \frac{1}{2\pi}\sqrt{\frac{1}{L_2 C_T}} \tag{2}$$

Where C_T is the sum of the Q_2 drain parasitic capacitances and the input capacitance of the distortion cancellation circuit. Q_2 width is set to 80μm and is connected in parallel to another transistor Q_5 so their drain current is added. The Q_5's biasing and sizing are both tuned to cancel the Q_2 g_{m3} transconductance component. Figure 2 illustrates how the g_{m3} cancellation technique works.

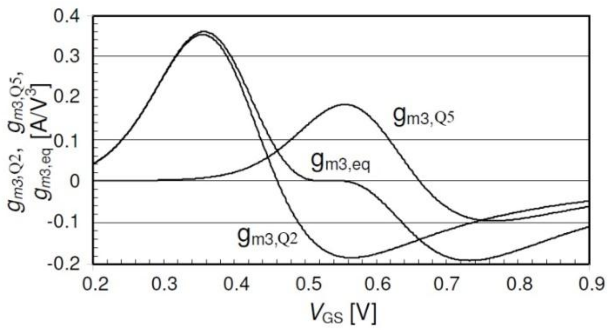


Figure 2. g_{m3} cancellation technique [8]

The total drain current is then passed to a distortion cancellation circuit through Port 1 for further IIP3 improvement as shown in Figure 3. The method proposed by [8] is implemented to enhance the linearity of the ultra-wideband LNA. The aforementioned method is composed of two parallel source-follower buffers. The R_1 resistor in Figure 3 is designed to be 10000Ω and all the coupling capacitors are chosen to be 1pF. The third-order nonlinearity current generated by the auxiliary path is equal in magnitude to the primary path Q_6 and Q_7, but 180° out of phase due to the design of the buffers Q_8 and Q_9. Biasing Q_6 in the negative g_{m3} region and Q_8 in the positive g_{m3} region will lead to phase inversion. The primary path through Q_6 and Q_7 requires high V_{gs} to bias them in strong inversion region where there is a negative g_{m3} region. The auxiliary path through Q_8 and Q_9 is biased through V_{g8} and V_{g9} to be in the weak inversion region where there is a positive g_{m3}. The resulting third-order nonlinearity currents are summed at the output leading to distortion cancellation.

Port 2 is connected to the output stage buffer, which consists of Q_3 and Q_4, which in turn, provides output matching to 50Ω by using the proper bias and device sizes. C_3 and L_4 are also used for proper matching and their values tuned to 3.45pF and 0.3378nH, respectively. The P_n tone source generates two fundamental frequencies at 5.79GHz and 5.81GHz separated by 20MHz frequency shift as an input to the UWB-LNA. The output of the UWB-LNA includes the fundamental signals f_1 and f_2 and the intermodulation signals generated in the UWB-LNA $2f_1 \pm f_2$ and $2f_2 \pm f_1$. By properly setting the devices widths and biasing, the third order nonlinearity currents generated in Q_8, Q_9 buffers were equal in magnitude and out in phase to the nonlinearity currents generated by Q_6, Q_7 buffer. The sum of these currents leads to the cancellation of the distortion currents generated by the UWB-LNA. If the distortion cancellation circuit is tuned to non-optimal values, then the sum of the currents will increase the power of the nonlinear components and hence the linearity will rapidly worsen.

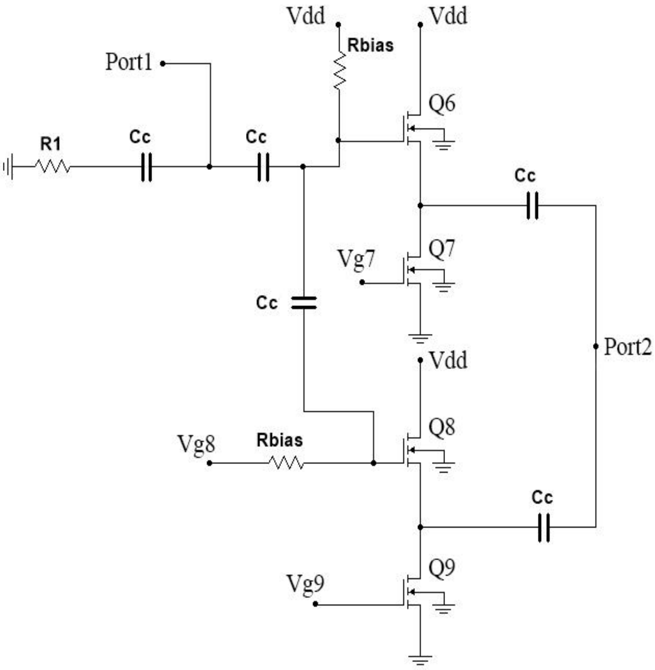
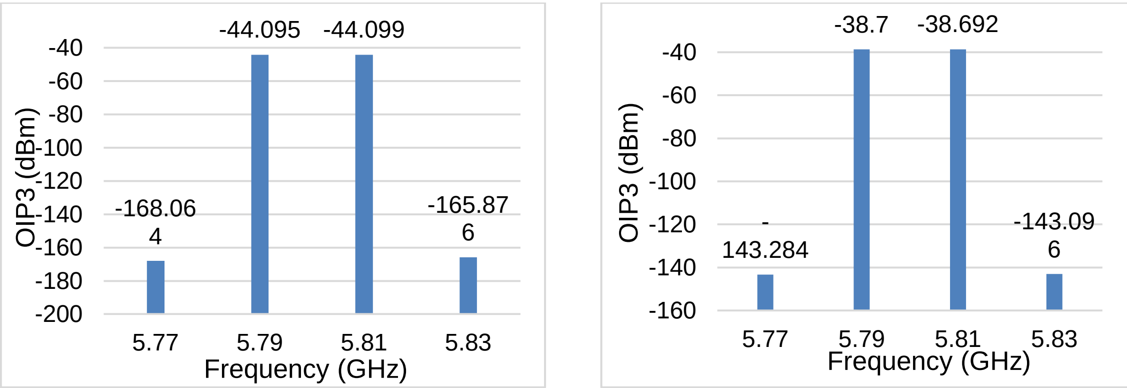


Figure 3. Intermodulation distortion circuit[8]

3. RESULTS AND ANALYSIS

The input power of the interferers enters to the proposed UWB LNA is -50dBm, hence the proposed method boosts the IIP3 to 12dBm as shown in Figure 4(a).



(a) (b)

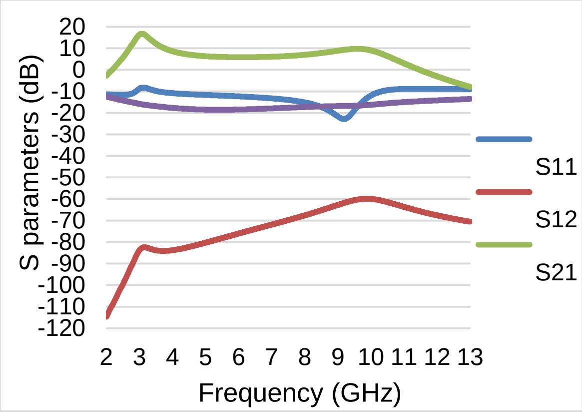
Figure 4. (a) Proposed UWB-LNA OIP3, (b) UWB-LNA OIP3

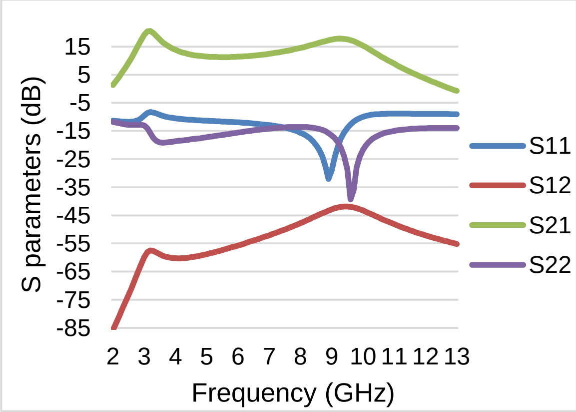
Where,

$$\mathrm{IIP3(dBm)} = \frac{\Delta P}{2} + P_{in} \tag{3}$$

The combination of previously reported linearization methods leads to an IIP3 of 12dBm. Figure 4(b) shows the UWB-LNA OIP3 without the linearization techniques and it exhibits an IIP3 of 2.2dBm. The S-parameters show that the insertion losses at input and output (S_{11} and S_{22}) are kept below

-9dB at the entire -3dB bandwidth. In addition, the insertion losses at input and output provide a gain of 6dB as shown in Figure 5(a). Figure 5(b) indicates that, without the proposed linearization technique, the UWB-LNA exhibits a gain of 11.304dB.

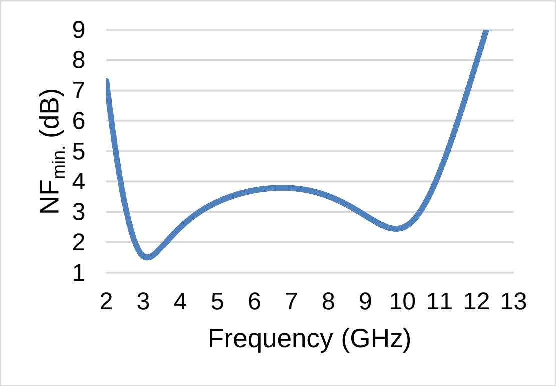


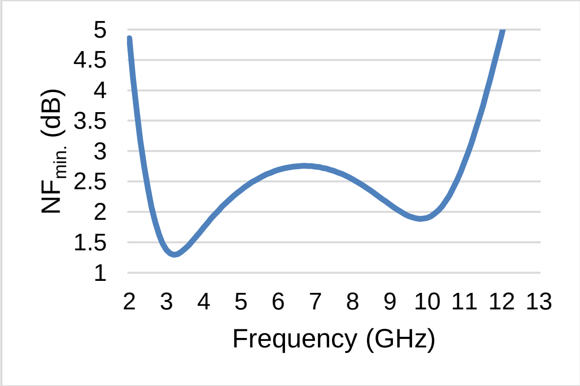


(a) (b)

Figure 5. (a) Proposed UWB-LNA S-parameters, (b) UWB-LNA S-parameters

The noise figure of the proposed UWB-LNA and UWB-LNA is 3.66dB and 2.645dB, respectively, at 5.8GHz as shown in Figure 6(a) and Figure 6(b). The proposed UWB-LNA circuit is stable along the entire band since the stability factor is greater than one and the stability measure is positive as shown in Figure 7(a) and Figure 7(b), respectively.





(a) (b)

Figure 6. (a) Proposed UWB-LNA NF, (b) UWB-LNA NF

The linearity and gain tradeoff is shown in Figure 8. Although the linearity is improved, the UWB-LNA gain deteriorates because of the reduced drain impedance (input impedance of the distortion cancellation circuit), where the gain of the common source stage can be expressed as:

$$A_v = \frac{-g_m Z_{in,d}}{1 + g_m Z_{o,Q_1}} \tag{4}$$

Where $Z_{in,d}$ is the input impedance of the distortion cancellation circuit, and $Z_{o,Q1}$ is the output impedance of the common gate stage.

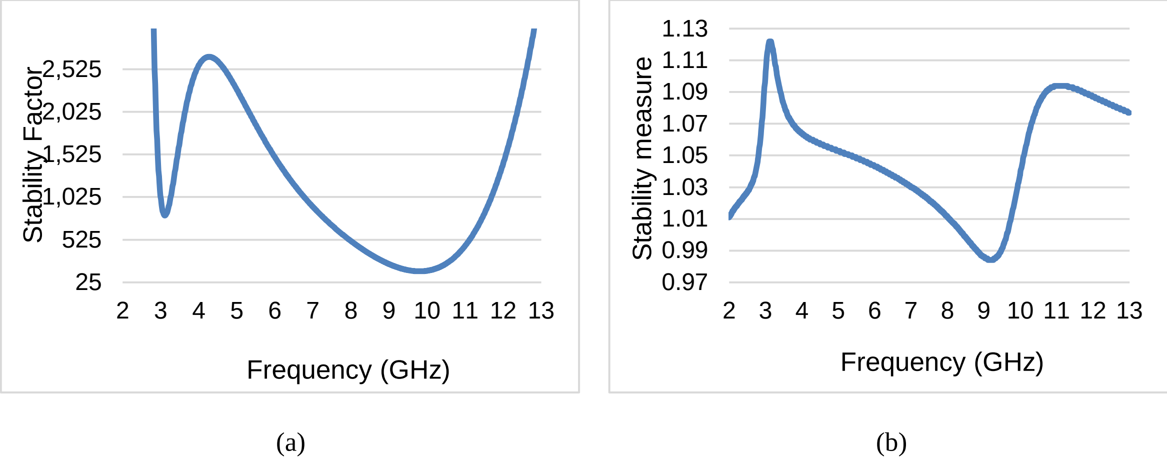


Figure 7. (a) UWB-LNA stability factor, (b) UWB-LNA stability measure

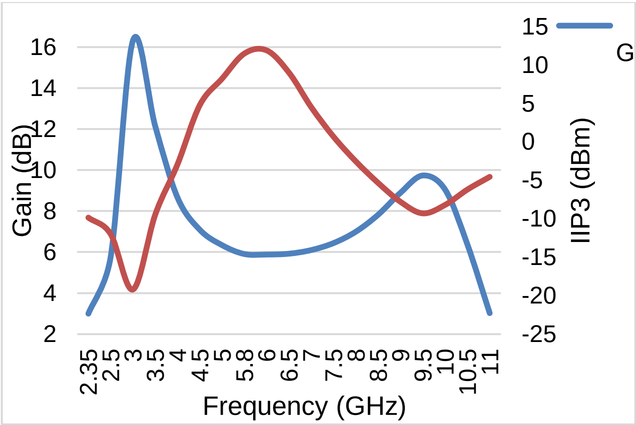


Figure 8. Gain and linearity vs. frequency tradeoff

The improved linearity is between 4.5GHz and 7GHz frequency band, which is equal to 4.8dBm. However, the maximum linearity at 6GHz equal to 12dBm. The worsened linearity is outside this band because the summation of the two buffers currents leads to increase an increase in the harmonics amplitude. Meanwhile, the total power consumption of the circuit, including the biasing of the output stage and the auxiliary transistor Q_5, is 24mW. The UWB-LNA, without the proposed linearization techniques, consumes 11.37mW, including the output stage.

The addition of the distortion cancellation circuit linearized the UWB-LNA at the cost of gain, increased power consumption, and noise. However, the linearity of the first stage in RF front receiver is critical when the channel is full of applications that utilize the entire bandwidth. Therefore, improved linearity is required to minimize the minimum detectable signal power and distinguish the weak signals. Brederlow and colleagues suggested a FOM that included the IIP3 of the LNA as in the following[10]:

$$FOM(-) = \frac{|S_{21}|(dB).IIP3(mW).F_o(GHz)}{|NF-1|(dB).P_{dc}(mW)} \quad (5)$$

Table 1 summarizes the performance of differently related recent researches compared with this work before and after the enhancement.

Table 1. Performance Comparison with Related Recent Researches

	Bandwidth (-3dB)	Gain (dB)	IIP3 (dBm)	Power Consumption (mW)	NF (dB)	Year	FOM
[This work]*	2.3 - 11	5.903@5.8GHz	12@5.8GHz	24	3.66		12.75
[This work]	2.5 – 10.9	11.304@5.8GHz	2.2@5.8GHz	11.37	2.645		8.425
[2]	2.4 – 11.2	14.8	-11.5	3.4	3.9	2012	0.935
[3]	3.1 – 4.8	13	-6.1	3.4	3.5	2012	0.64
[6]	0.1 – 2.2	12.3	-10	0.4	4.9	2016	1.656
[7]	0.6 – 4.2	14	-10	0.25	4	2016	6.72
[11]	30 – 50	21.5	0	20.4	3.8	2013	7.53
[12]	2.7 – 6.7	15	-2	8.8	3.07	2013	2.1
[13]	3 – 5	16.7	-4	13	2.1	2013	0.93
[14]	3.1 – 10.6	10.7	-2.9	8.3	2.2	2015	4.13
[15]	2.8 – 10.6	13.4	-0.310	5.74	2.98	2015	8.563
[16]	3.6 – 11.2	14.5	-15.7	14.5	3.4	2013	0.12
[17]	3.1 – 10.6	12.25	2.5	18	2.5	2014	6.05
[18]	1.7 – 15.4	12.9	-5	10.35	1.7	2014	7.7
[19]	0.1 – 2.25	25.02	-7.8	3.24	2.37	2017	2
[20]	3.1 – 10.6	20	-22	4.33	1.034	2015	6.43
[21]	2.35 – 9.37	10.3	-4	9.97	3.68	2015	1.1
[22]	3.5 – 5	14	4	21	3.9	2015	0.9
[23]	3.5 – 9.25	15	-12	9.6	2.4	2014	0.4
[24]	2.9 – 12.7	17.8	-11.5	9.67	4.8	2014	0.336
[25]	1 – 12.5	15.2	-0.2	18	2.2	2014	7.73
[26]	0.1 – 10	24	-13.5	8.6	2.6	2013	0.77

*means the LNA after enhancement

4. CONCLUSION

The combination of two or more linearization methods leads to more improvement in IIP3 (linearity) as well as the receiver's performance and sensitivity. The combination of two linearization methods on a UWB-LNA shows about 10dBm IIP3 improvement, 5dB gain variation, and less than -9dB input/output return losses at the entire bandwidth for both non-linearized and linearized UWB-LNA circuits. The suggested technique achieves 5.903dB, 3.66dB gain and noise figure, respectively. In addition, the linearized UWB-LNA consumes 24mW supplied from 1.5V voltage source including the output stage, distortion cancellation circuit, and auxiliary transistor Q5. The ADS optimizer tool optimizes the biasing gate voltages and FETs widths using quasi-newton optimization method to achieve higher IIP3 improvement for the designed UWB-LNA circuit. If high linearity is a critical design criterion, then a better IIP3 performance could be obtained through combining more linearization techniques on the same working LNA.

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