A Novel IP3 Boosting Technique Using Feedforward Distortion Cancellation Method for 5GHz CMOS LNA

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Abstract — **Low noise amplifier(LNA) in many wireless and wireline communication systems must have low noise, sufficient gain and high linearity performance. This paper presents a novel IP3 boosting technique using Feedforward Distortion Cancellation(FDC) method. Through this technique, the IIP3 of LNA can be boosted from +5dBm, which is reported in most public literature to date, to +21dBm, which is firstly reported to this day, without any noise and gain degradation. In addition, noise figure can be reduced about 0.4dB and gain increased 0.4dB due to the additional gain path.**

I. INTRODUCTION

Low noise amplifier(LNA) in many wireless and wireline communication systems, such as WLAN and CDMA, must have low noise, sufficient gain and high linearity performance[1]. To date, LNA designers always adopt two mode design strategy to achieve all the above goals, one is high gain, low noise but low linearity for small desired signal with small interference, another is low gain, high linearity but high noise for large desired signal with large interference. It seems high linearity must sacrifice low noise. But it is well known the situation that small desired signal with large interference always occurs in communication systems[2]. That means LNA must achieve high linearity and low noise simultaneously for these demanding systems.

To accomplish this, Ding and Harjani propose a harmonic distortion technique[3]. But actually, this technique also sacrifice noise because of the auxiliary LNA takes away almost half of the input signal from antenna and dumps them to VDD instead of output node. That means the noise figure is degraded about 3dB,which is unacceptable for a LNA.

This paper firstly proposes a Feedforward Distortion Cancellation(FDC) technique to achieve high linearity LNA, which has +21dBm IIP3, without any noise and gain degradation.

The principle of FDC technique is illustrated in section II. Then the details of circuit design is presented in section III. Section IV gives out the experimental results of a 5GHz LNA design in which this technique is applied. Finally, section V gives a brief summary.

II. PRINCIPLE OF FEEDFORWARD DISTORTION CANCELLATION TECHNIQUE

Theoretically, any small signal amplifiers, such as LNA, manifest nonlinearity characteristic, which can be described with power series as following:

$$v_{out} = a_0+a_1v_{in}+a_2v_{in}^2+a_3v_{in}^3+\dots\dots \quad (1)$$

in which a_0 is the DC offset, a_1 is the small signal gain, and a_3 is the most important third order distortion coefficient. From MOSFET physical model analysis, it is well known that a_1 is negative while a_3 is positive for common source configuration, which is the most prevalent LNA topology. In addition, the following relation exist:

$$|a_1|>>|a_3| \quad (2)$$

From the above expressions, an idea naturally comes into mind. If the original LNA output, v_{out}, multiplied by v_{in}^2, then we get $a_1v_{in}^3$, which has the same order as $a_3v_{in}^3$ while maintaining reverse sign. If a proper scaling down is done to $a_1v_{in}^3$, then an additional third order component is acquired, which has the same amplitude and reverse sign compared to $a_3v_{in}^3$. Thus this additional third order component can be used to cancel the original third order distortion. A high linearity LNA is accomplished due to this distortion cancellation.

To realize this high linearity LNA, the original LNA must be divided into two signal path, which is shown in Fig. 1. One is the same as the original LNA signal path, another feedforward signal path is used to generate additional third order component, which uses two coupler to do $a_1v_{in}^3$ component scaling down and MOS multiplier to do multiplication. Two time delayer is exploited to compensate the time delay difference between two signal path. Due to equation (2), the coupler ratio is quite large so that only less than twentieth signal of v_{in} and v_{out} is coupled to the additional feedforward signal path. That means the additional signal path almost contributes no noise to the whole LNA even this path has much loss. That is why the proposed LNA architecture has high linearity while maintaining low noise and high gain characteristic. Because of its very little noise, if this path has some gain, the whole gain and noise figure will be improved for this additional gain. This is quite an interesting result which will be shown later on.

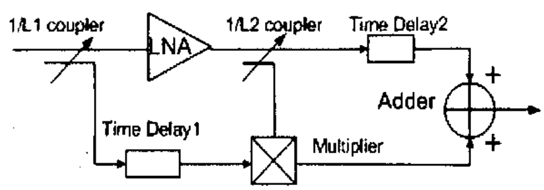

Fig. 1. IP3 boosting technique using FDC method.

III. DETAILS OF CIRCUIT DESIGN

Although the idea of feedforward distortion cancellation technique seems simple, great care must be taken when realizing it with practical circuits for the demanding requirements of time delay matching and proper scaling down coupler coefficient. The formal determines the phase property of the generated third order component and the latter determines the amplitude property.

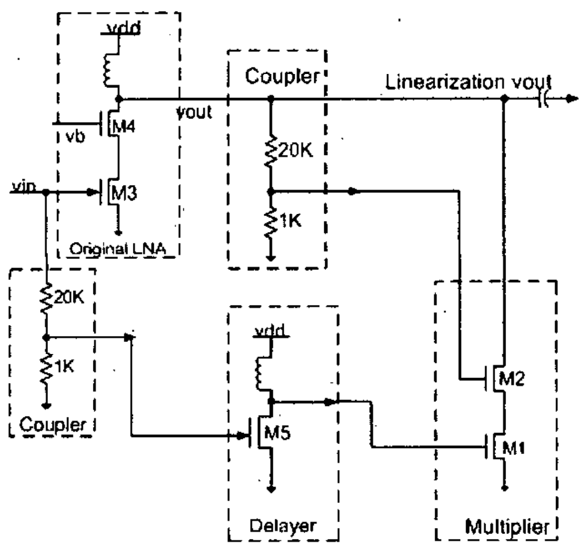

Fig. 2. Simplified schematic of IP3 boosting technique.

The original LNA design consideration is the same as traditional LNA. To simplify the circuit and minimize noise, two large resistive dividers are used as couplers. Common source amplifiers with unit gain and inductive load are used as time delayers. It is critical to optimize the delay constant and coupler coefficient in order to achieve best cancellation performance. The simplified schematic of this high linear LNA is shown in Fig. 2.

The MOSFET multiplier is shown. The original LNA output is coupled to M2, which acts as a source follower. The coupled signal of vin is fed to M1, which is in saturation. Thus the following ac signal relations exit:

$$v_{gs} = v_{in} \tag{3}$$

$$v_{ds} = v_{out} \tag{4}$$

v_{in} and v_{out} is referred to the original LNA input and output signal. Due to the channel length modulation effect of M1, the output signal current of the multiplier is:

$$I_m = \beta_{M1}(v_{in}-V_{th})^2(1+\lambda v_{out}) \tag{5}$$

$$\beta_{M1} = \mu_0 C_{ox} W/2L \tag{6}$$

λ is channel length modulation coefficient. Obviously from equation (5), an additional third order component of v_{in} is generated through $v_{in}^2 v_{out}$ term, which is adjusted by time delayer and coupler to cancel the third order nonlinearity of original LNA which is outphase to it. If the original LNA output voltage is described as equation (1) The original LNA signal current and multiplier signal current is re-formulated:

$$I_{out} = b_0+b_1 v_{in}+b_2 v_{in}^2+b_3 v_{in}^3+\dots\dots \tag{7}$$

As just less than twentieth of v_{out} is coupled to multiplier, v_{out} can be approximated by $a_1 v_{in}$ without losing accuracy. After processing these expressions, a simplified formula of I_m is achieved:

$$I_m = \beta_{M1}\lambda\ (a_1 v_{in}^3-2a_1 v_{th} v_{in}^2+a_1 v_{th}^2 v_{in})/L \tag{8}$$

$$L = L_1 L_2 \tag{9}$$

Because $a_0 \sim a_n$ have the same sign with $b_0 \sim b_n$, respectively, thus the first order component of total current is increased by $\beta_{M1}\lambda a_1 v_{th}^2 v_{in}/L$ term, the third order distortion is decreased by $\beta_{M1}\lambda a_1 v_{in}^3/L$ term. If the coupler coefficient L and time delay are properly chosen, the third order distortion can be totally cancelled while maintaining an additional gain due to $\beta_{M1}\lambda a_1 v_{th}^2 v_{in}/L$ term. From the analysis, we can not only achieve high linearity without noise and gain degradation, but also expect a little improvement in noise and gain performance.

Finally, a side effect of this technique should be taken care of. Analysis above can be valid only when the input signal is not too large, such as less than –20dBm. If the input signal is too large, v_{out} can't be approximated by $a_1 v_{in}$ only. Because $a_3 v_{in}^3$ multiplied by v_{in}^2 can derive a fifth order term. This term would increases with input power at a slope of 5, manifest itself and dominate the distortion when the signal is too large. However, worry about this side effect is not necessary. When the signal is larger than –20dBm, low noise performance of LNA is no longer needed and the traditional signal dumping method[4] can be used to resolve this difficulty.

IV. Experimental Results Analysis

To validate all the analysis above, a 5GHz LNA for WLAN application is designed with UMC0.25um CMOS technology. All the experiments are carried out under Agilent ADS software.

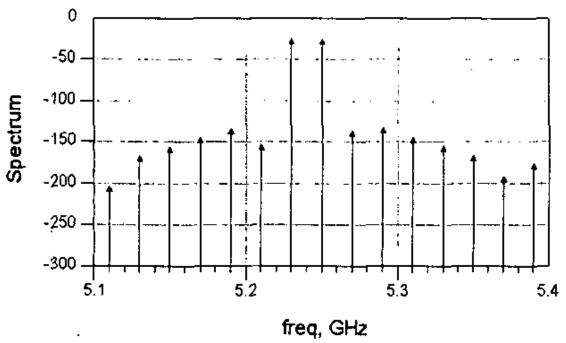

Fig.3. Spectrum of two tone test at input power=-40dBm.

In order to get best cancellation effect, optimization is carried out on delay time and coupler coefficient when the input signal is –40dBm. The input two tones are 5.23GHz and 5.25GHz, respectively. Fig. 3 shows the output

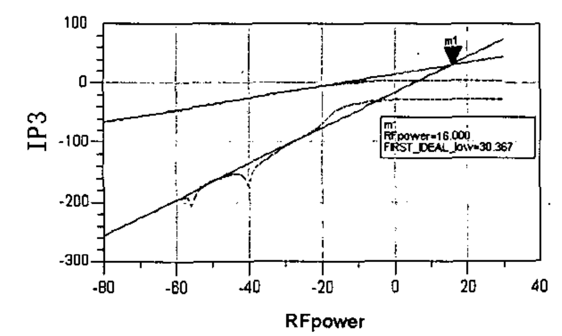

Fig. 4. IIP3 extrapolation when input power sweeping.

spectrum of the LNA after IP3 boosting. It is –25.64dBm at 5.23GHz and –153.98dBm at 5.21GHz. The extrapolation intercept point of first order and third order curve is +21.18dBm. This is a firstly reported LNA in public literature which has an IIP3 beyond +20dBm. As the input power sweeps from –80dBm to 0dBm, curves of first order and third order components versus input power are plotted in Fig. 4. As the optimization is just done to –40dBm input signal, this plot acquires +16dBm IIP3, which is still the highest IIP3 achieved at about 1.2dB noise figure. Note the sharply increase of third order component after –20dBm, it is due to the fifth order term stated previously.

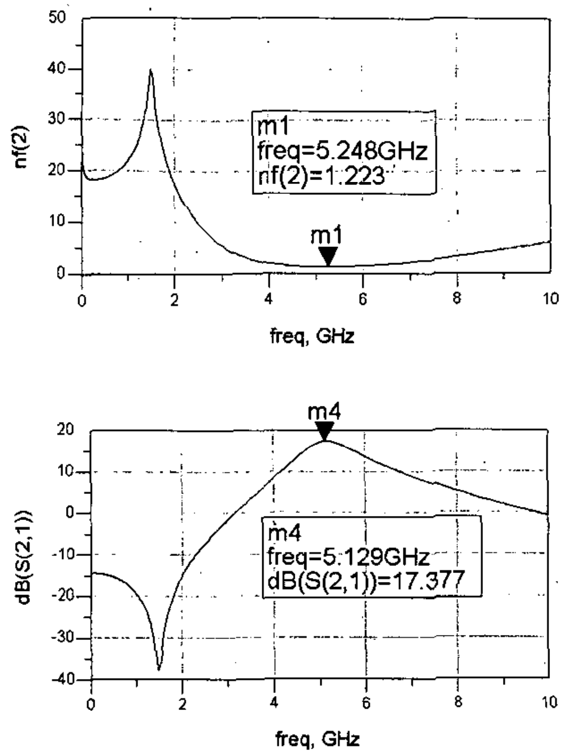

Fig. 5. (a) NF (b) S21

Fig. 5(a) shows the NF of the whole circuit. As stated previously, only less than twentieth input signal and output signal of the original LNA is coupled to the feedforward distortion generation path, almost no noise contribution of this additional signal path. The NF is 1.22dB while it is about 1.7dB before linearization. It is because the feedforward distortion generation path provide about 0.4dB gain while contributes much less noise so that the overall output SNR and NF is improved by 0.4dB. This is quite an interesting result when you think about people always sacrifice noise to achieve linearity in so many years. Fig. 5(b) shows the power gain of this linear LNA. It has about 17.4dB gain, which is also larger than most other high linearity LNAs although their IIP3 is much lower than this one.

Other experimental results are: s11 and s22 both are about –23dB, s12 is about –32dB. MuPrime is always greater than 2 at the whole frequency range and about 5 at the working frequency band.

V. Conclusion

This paper firstly proposes a novel IP3 boosting technique using Feedforward Distortion Cancellation (FDC) method. This technique can boost IIP3 of LNA from +5dBm to +16~+21dBm without any noise and gain degradations. In addition, the noise figure of LNA is reduced about 0.4dB because the auxiliary signal path provides about 0.4dB gain and much less noise. The whole LNA finally has 17.4dB power gain and 1.22dB noise figure while maintaining +16~+21dBm IIP3.

Acknowledgement

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