A Direct Conversion Merged LNA-I/Q-Mixer With Noise Reduction Using Dual Cross Coupling for WiMAX/WiBro Applications

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***Abstract*—A direct conversion merged low noise amplifier (LNA) and I/Q-mixer with new noise reduction technique is presented in this letter. The merged LNA-I/Q-mixer employs a dual capacitor cross coupling (CCC) technique to improve the circuit noise performance. The first CCC is applied at the transconductance stage of the LNA to increase the effective transconductance, which in turn lowers the noise figure and decreases the current consumption. The second CCC connection is applied at the cascode stage of the LNA, which can reduce the influence of the noise current from cascode transistors. The simulation shows the proposed combination of the LNA and I/Q-mixer configuration with the dual CCC technique can achieve NF 3 dB better than that of conventional merged topologies in a wideband application. The measured NF is lower than 4.55 dB from 2.3 to 2.7 GHz. In addition, low-power and low-cost circuit is realized due to current-reused and inductor-less design at the interface of the LNA and I-Q mixer. The core circuit only consumes 16.83 mW and occupies 0.16 mm^2 area.**

***Index Terms*—Cross coupling, direct conversion, I/Q-mixer, low noise amplifier (LNA), noise reduction, wireless broadband (WiBro), worldwide interoperability for microwave access (WiMAX).**

I. Introduction

THE IEEE 802.16e mobile Worldwide Interoperability for Microwave Access (WiMAX) and Wireless Broadband (WiBro) systems adopt the orthogonal frequency division multiple access (OFDMA) modulation technique, and also provide high speed and high data rate application. The tendency toward low power, low cost, and low noise for a direct conversion front-end receiver is required in the WiMAX/WiBro applications. The merged low noise amplifier (LNA) and I/Q-mixer is one of the solutions to meet these requirements. There had been several types of merged topologies. The first one stacks LNA and I/Q-mixer with the common source/emitter (CS/CE) input configuration [1] to save power and demonstrate a good noise figure (NF), while the topology shows a limited bandwidth and requires additional inductors. Although multi-element matching networks can perform a wider bandwidth, passive components occupy a fairly large chip area. In contrast, the combination of LNA and I/Q-mixer with the common gate/base (CG/CB) input configuration can be considered as a candidate for a wide input matching, low power, and low cost application. However, CG/CB amplifiers suffer from higher NF than the topology using CS/CE amplifier. Using folded technique to convert the stacked circuit into a cascaded one [2], [3] is the second means, which decreases the power consumption to obtain low voltage design. However, the loaded inductor increases overall chip size. A third way applies an on-chip transformer [4]. The conversion loss and larger chip size from the transformer limit its application. A BLIXER topology [5] with noise canceling [6] is another solution. In this stacked configuration, unbalanced transconductance from differential transistors is necessary to lower noise contribution.

In this letter, the merged LNA and I/Q-mixer is proposed and the CCC technique is incorporated simultaneously in the transconductance and cascode stages, which reduces the shot noise in collector current and the equivalent noise current from main and cascode transistors, respectively.

II. Merged LNA and I/Q-Mixer

The merged LNA and I/Q-mixer with the dual CCC configuration applied at the transconductance and cascode stages can improve the noise performance, as shown in Fig. 1. The C_{C1} and C_{C2} are employed to allow differential input voltage to drop across the base and emitter terminals of each input transistor. Because the loop gain of the positive feedback path is smaller than unity, the condition of oscillation will not happen. Moreover, The effective transconductance is boosted by means of the feed forward connection, thereby increasing the conversion gain and reducing the NF [7], [8]. If the input signals are sinusoidal signals, the overall conversion gain of the merged topology can be expressed as follows:

$$A_{\text{conv.}} = \frac{2}{\pi}(1+A)g_{m1}R_{\text{IF}} = \frac{2}{\pi}G_{m1}R_{\text{IF}} \quad (1)$$

where the coupling factor A $= C_{C1}/(C_\pi + C_{C1})$ is approximately equivalent to 1 if the cross couple capacitance C_{C1} is larger than the junction capacitance C_π, and G_{m1} is the effective transconductance of the transistor Q_1, and R_{IF} is the load resistor. To achieve input impedance matching, the boosted G_{m1} is designed as inverse of the source resistance ($R_S = 50$ ohm). The conversion gain can be expressed as $(2/\pi)(R_{\text{IF}}/R_S)$. Since R_{IF} is only required to be $>353\ \Omega$ to obtain 20 dB conversion gain, the entire headroom is adequate for voltage drop across the load resistor and stacking three

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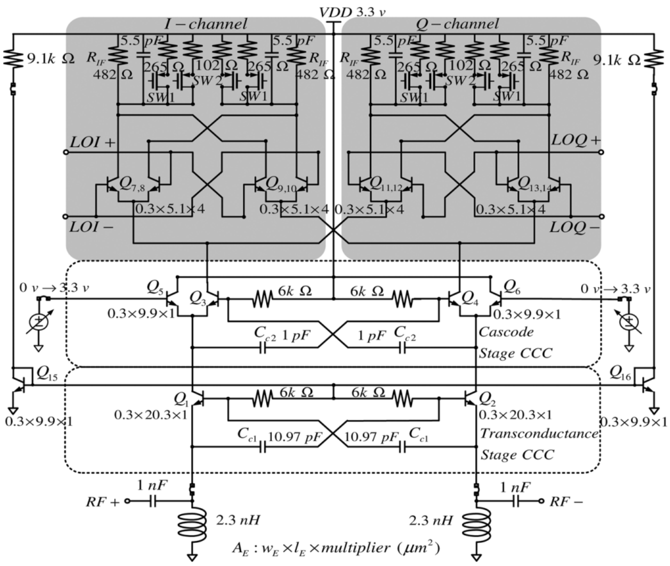

Fig. 1. Schematic of the merged LNA and I/Q-mixer with dual CCC.

transistors. In addition, gain-controlled mechanism is also incorporated in this merged topology. Four gain states can be performed by switching the load resistors and steering current path from the cascode stage. The highest gain mode operates at maximum load impedance and without steering current. By switching on only SW1 or on SW1 and SW2 simultaneously, shown in Fig. 1, the reduced load impedance causes the lower gain modes. The lowest gain mode is performed by reducing load impedance and by sharing current on transistors Q_5 and Q_6 from 0 V to VDD simultaneously.

The noise performance is a significant factor for the merged LNA-I/Q-mixer. Assuming a noiseless switching-quad from mixer, Fig. 2 shows the small signal equivalent noise model of a CB cascode amplifier with a load resistor, and the corresponding NF is derived as follows [9]:

$$\mathrm{NF} \approx 10 \cdot \log \left(1 + \frac{r_{b1} + r_{e1}}{R_S} + \frac{g_{m1} R_S}{2\beta_0} + \frac{1}{2 g_{m1} R_S} + \frac{g_{m1} R_s}{2} \left(\frac{\omega_o}{\omega_T} \right)^2 + \frac{(C_{\text{para.}} \omega_o)^2}{2 g_{m1} g_{m3}^2 R_S} \left(\frac{\omega_o}{\omega_T} \right)^2 + \frac{1}{g_{m1}^2 R_{\text{IF}} R_S} \right) \quad (2)$$

where r_{b1} and r_{e1} are the base and emitter resistors, g_{m1} and g_{m3} are the transconductance from transistors Q_1 and Q_3, β_o, ω_o and ω_T are the current gain, resonant frequency and transition frequency, respectively, and $C_{\text{para.}}$ is the parasitic capacitance between Q_1 and Q_3.

Equation (2) reveals that the noise contributions of the second, third, fifth, and last terms are negligible for its small value. Accordingly, the dominant contributions for a CB cascode amplifier are determined by the fourth and sixth terms. To further improve the NF, the first CCC is employed at the transconductance stage to boost g_{m1} and then the fourth term can be expressed as $1/(2(1+\mathrm{A})\mathrm{g_{m1}R_S})$, which is decreased by a factor of $(1+\mathrm{A})$. The second CCC is utilized at the cascode stage, which behaves like another CB input configuration to increase its effective transconductance. The noise contribution from the sixth term is therefore reduced if g_{m1} and g_{m3} are boosted and $C_{\text{para.}}$ is minimized. The parasitic capacitance $C_{\text{para.}}$ can be alleviated by compact layout of the transconductance and cascode transistors [10]. The simulated NF of the merged LNA and I/Q-mixer with dual CCC mechanism, as depicted in Fig. 3, exhibits a 3 dB improvement from the conventional merged topology without dual CCC under the same bias condition. These simulated comparisons demonstrate that the proposed dual CCC can indeed improve the noise performance.

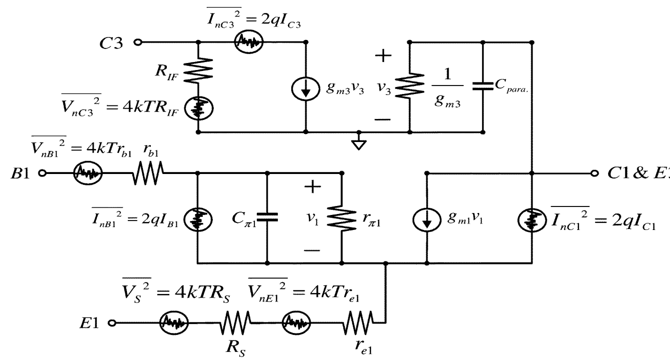

Fig. 2. Small signal equivalent noise model of a CB cascode amplifier.

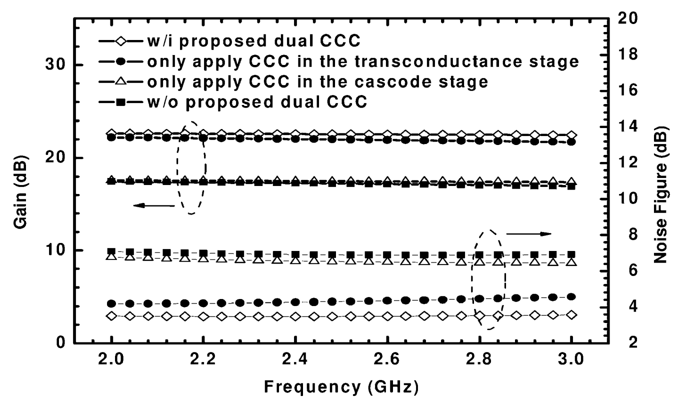

Fig. 3. Comparison of simulated NF performance of the merged LNA and I/Q-mixer with and without the dual CCC technique.

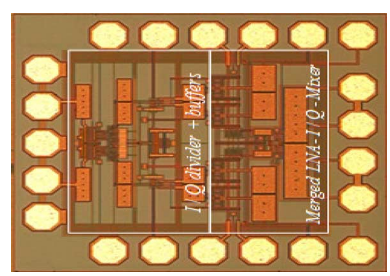

Fig. 4. Chip photograph.

III. Measurement Results

A direct conversion merged LNA and I/Q-mixer with LO transmit path for a WiMAX/Wibro front-end receiver is fabricated using TSMC 0.35 um SiGe BiCMOS technology. The test

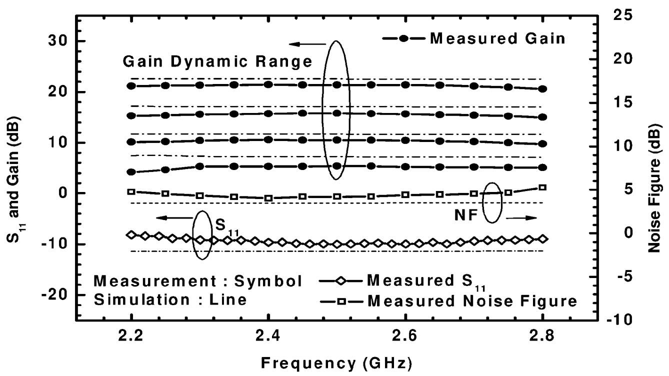

Fig. 5. S_{11} in dB, gain response, and NF for IF $=$ 10 MHz.

TABLE I
CHIP PERFORMANCE AND COMPARISON WITH OTHER FRONT-END RECEIVER

Parameter	This work	[3]	[4]	[5]
Application	WiMAX/ WiBro	SDR	WLAN	SDR/ UWB
Configuration	Stacked	Folded	Trans-f ormer	Stacked
3-dB Bandwidth (GHz)	1.3 ~ 3.3	0.1 ~ 3.85	5.73 ~ 5.83	0.5 ~ 7
Gain (dB)	21.4	20	34.61	18
Gain State (dB)	21.4/15.8/ 10.5/5.4	20	34.61	18
IP1dB (dBm) (Highest/Lowest gain)	-16 / -10	-12.83	-19.1*	-12.6*
IIP3 (dBm) (Highest/Lowest gain)	-6.5 / -0.5	-3.23*	-9.5	-3
S_{11} (dB)	< -9	<-10	< -25	-10
NF_{dsb} (dB) (Highest/Lowest gain)	4 ~ 4.55 9.9 ~ 10.8	5.4**	4.15	5.5
Chip Size (mm^2) LNA+IQ-Mixer	0.16	0.88	0.8	<0.01
Power (mW) LNA+IQ-Mixer	16.83	9.8	12	16
FOM	0.21	0.74	0.03	0.63

* Estimated from IIP3 = IIP1 + 9.6 dB
** Estimated from $NF_{dsb} = NF_{ssb}$ - 3 dB

chip photograph is displayed in Fig. 4. Due to the inductor-less design, the chip only occupies 0.16 mm^2 of chip area for the merged LNA-I/Q-mixer. The chip is measured by mounting the die directly on a four layer FR-4 PCB. The signal generator generates an RF and LO signal, fed into the LNA inputs and an I/Q divider, respectively, by external 180° hybrid baluns. The power consumption of the core circuit is 5.1 mA.

Fig. 5 presents the full band frequency response of the simulated input return loss, front-end receiver gain, and NF in comparison with the measurement results. The measured conversion gain is approximately 21.4 dB with an IF frequency of 10 MHz. The gain flatness of less than 0.3 dB can be achieved from 2.3 to 2.7 GHz. In addition, the merged LNA and I/Q-mixer performs four gain states which range from 21.4 dB to 5.4 dB. The measured input return loss which exhibits a broadband characteristic is below -9 dB at the desired frequency band and also remains around the same level in the different gain states because of the CB input configuration. The de-embedded NF of the front-end receiver from the loss of the balun can be less than 4.55 dB due to the proposed dual CCC technique while the measured IF frequency is fixed at 10 MHz. For the measurement of linearity, the IP1dB is -16 dBm and -10 dBm at the highest and lowest gain state, respectively. The IIP3 achieves -6.5 dBm and -0.5 dBm, respectively.

Table I summarizes the measured performance of the receiver and compares it with the prior works [3]–[5]. Although the combined LNA-I/Q-mixer, current-reused, and inductor-less design are also employed in [5] which demonstrates an excellent performance on chip area and power dissipation, the NF based on the proposed dual CCC technique in this study shows an approximately 1 dB improvement. The configuration using folded [3] or transformer [4] indicates a larger chip area than the stacked ones. To evaluate the performance, a figure of merit (FOM) is described as follows:

$$\mathrm{FOM}[-] = \frac{\mathrm{Gain}[abs] \cdot \mathrm{IIP3[mW]} \cdot \mathrm{BW[GHz]}}{(\mathrm{NF}-1)[abs] \cdot P_{\mathrm{dc}}[\mathrm{mW}]}. \quad (3)$$

IV. CONCLUSION

A merged LNA-I/Q-mixer for dual mode WiMAX and WiBro applications with noise reduction technique is proposed. The merged LNA and I/Q-mixer achieves low power and low cost as a result of compact and concurrent design. Furthermore, the noise performance is improved by the proposed dual CCC technique which is applied at the transconductance and cascode stages of the LNA. To demonstrate the properties of the CCC network, the merged LNA and I/Q-mixer is analyzed, designed, and measured.

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