Original Research Article

Differential Active Balun Design for WiMAX Applications

ABSTRACT

The paper presents a design and simulation study of a differential active balun circuit implemented in a standard 90nm complementary metal-oxide semiconductor (CMOS) process. The active balun design is intended for Worldwide Interoperability for Microwave Access (WiMAX) applications operating at frequency 5.8GHz and with supply voltage of 1V. Measurements are taken for parameters such as gain difference, phase difference, and noise figure. The differential active balun design achieved gain difference of less than 0.23dB, phase difference of 180° ± 3.4°, and noise figure of 9.78dB, which are comparable to past active balun designs and researches. Lastly, the design achieved a low power consumption of 3.6mW.

Keywords: Differential active balun; gain difference, phase difference, WiMAX

1. INTRODUCTION

The radio frequency (RF) front-end of a wireless receiver is of particular interest to many RF integrated circuit (RFIC) designers and researchers as it proves to be a critical part in many wireless communication systems such as bluetooth, wireless fidelity (WiFi), and worldwide interoperability for microwave access (WiMAX). A typical receiver is illustrated in Fig. 1 block diagram.

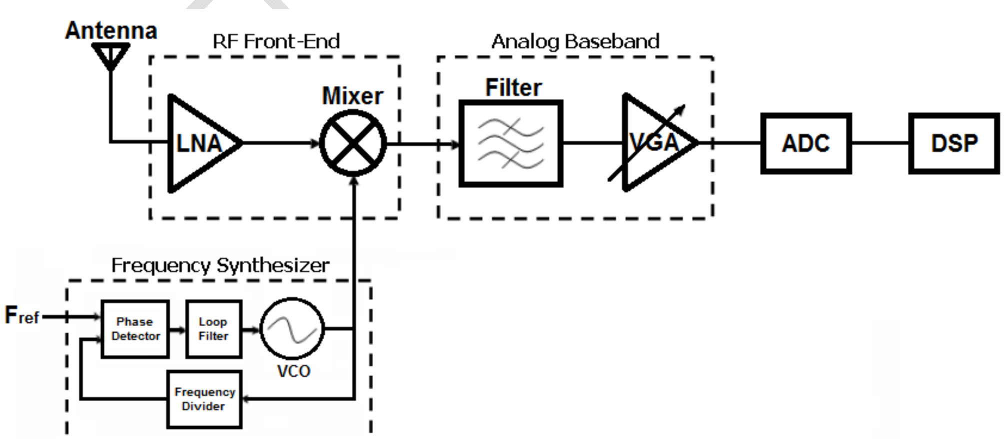

Fig. 1. Block diagram of a wireless receiver

Some of RF front-end circuits are often designed as differential circuits. Fully-differential approach is usually preferred in RFIC design due to its advantages, particularly the high immunity to common-mode noises, rejection to parasitic couplings, and increased dynamic range [1] [2]. In order to supply input signal to differential circuits, a building block capable of supplying balanced differential signals is needed without sacrificing the performance of the overall system in terms of gain, noise figure, and linearity. Active balun (balanced-unbalanced) is capable to perform the necessary tasks.

A balun circuit is a type of transformer that converts signals that are single-ended or unbalanced with respect to ground into signals that are differential or balanced with respect to ground, and vice versa. Baluns can be classified as either active or passive baluns depending on the devices used. Active baluns, although unidirectional and more complex to implement, are preferred over their passive counterparts because they can produce gain, occupy less chip area and can operate at higher frequencies [1].

Active balun circuit can be used as the first block of the WiMAX receiver front-end to supply differential signal to a differential low-noise amplifier (LNA). It can also be used to supply differential signal to a mixer. Fig. 2 shows the active balun circuit as an intermediate block between the LNA and the mixer. Note that the configuration depends on the gain, noise figure (NF), and linearity requirements of the system. Since LNA is the first block in the receiver front end, it is critically designed with high gain of at least 25dB and noise figure of less than 2dB. Based on past researches, active balun has relatively high noise figure and lower gain performance compared to LNA, hence cannot be considered as the first block in the receiver front-end. Ultimately, the challenge is to design an active balun as an intermediate block to allow the LNA's output to connect with a differential mixer's input, with performance conforming to the requirement for the WiMAX receiver front-end.

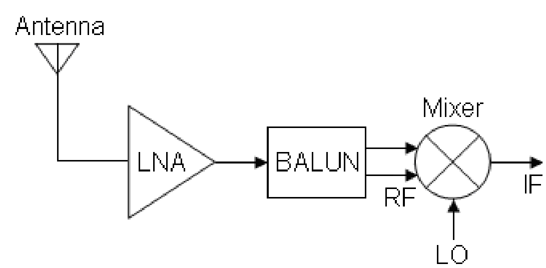

Fig. 2. Active balun as intermediate block between LNA and mixer

2. ACTIVE BALUN DESIGN

In this research paper, a differential active balun is designed and implemented in a standard 90nm complementary metal-oxide semiconductor (CMOS) technology. The supply voltage (V_{DD}) for the design is set to 1V. The lengths (L) of all transistors are set to 100nm, which is the minimum allowed channel length for the technology used. Transistor widths (W) are carefully computed to ensure the operation of all the transistors at saturation. As mentioned earlier, the paper deals with the design of active baluns as intermediate block between LNA and mixer in the WiMAX receiver front-end. Table 1 summarizes the target specifications of the active balun design. These values are based from past active balun researches and from the summary of parameters as per WiMAX standard [3].

Table 1. Minimum target parameter values for the differential active balun design

Parameters	Value
Frequency	5.8GHz
Gain difference	< 1dB
Phase difference	180° ± 10°
Noise figure	< 10dB
Power consumption	< 10mW

Two most important parameters of the active balun are the gain difference and phase difference. Gain difference is the difference of the gains from the two output nodes of the active balun while the phase difference is the difference between the phase of the non-inverting output node (RFout1) and the phase of inverting output node (RFout2) of the active balun. Noise figure on the other hand, is the measure of the amount signal-to-noise-ratio (SNR) degradation introduced by the circuit as seen in the output.

The differential active balun, as shown in Figure 3 is composed of 3 transistors namely M1 and M2 for the differential output, and M3 for the tail current. The input signal is applied at the input of one of the differential pair transistors and will ideally split equally between the pair with same amplitude and 180° phase shift. This active balun topology is capable of producing gain.

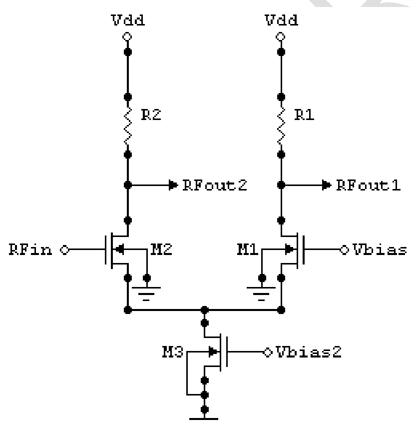

Fig. 3. Schematic diagram of differential active balun

To have a larger headroom for transistors M1 and M2, transistor M3 which acts as the tail current that supplies the M1 and M2 branches should maintain just enough drain-to-source voltage $V_{DS}3$. Setting V_{DS} with V_{DSAT} or V_{OV} for all transistors could maximize the output swing for outputs RFout1 and RFout2. With supply voltage V_{DD} = 1V, overdrive voltage (V_{OV}) set to 200mV, threshold voltage V_t set to 400mV, and with the two outputs balanced, input and output DC voltages are calculated in Eq. (1) to (4).

$$V_{DD} > V1 \geq V_{DSAT1} + V_{DSAT3} \quad \rightarrow \quad 1V > V1 \geq 0.4V \qquad \text{Eq. (1)}$$

$$V1 = V_{RFout1} = \frac{V_{DD} + V_{OV1} + V_{OV3}}{2} = \frac{1V + 0.4V}{2} = 0.7V \qquad \text{Eq. (2)}$$

$$V_{DD} > V2 \geq V_{DSAT2} + V_{DSAT3} \quad \rightarrow \quad 1V > V2 \geq 0.4V \qquad \text{Eq. (3)}$$

$$V2 = V_{RFout2} = \frac{V_{DD} + V_{OV2} + V_{OV3}}{2} = \frac{1V + 0.4V}{2} = 0.7V \qquad \text{Eq. (4)}$$

Branch currents flowing through M1 and M2 set the desired transistor dimensions to satisfy the performance parameters of the active balun, ensuring the allowed total power consumption. However, the impedance of M3 which acts as a current source is not as high as required because of non-ideality caused by parasitics at high frequency. This results in unequal signal distribution, hence affecting the gain balance and phase difference of the circuit. To mitigate this imbalance with transistor dimensions set identical for the branch transistors M1 and M2, adjustments are done at output loads R1 and R2. Moreover, the design is optimized to meet the target performance specifications suitable for WIMAX receiver. All active designs are implemented in a standard 90nm CMOS process using Cadence Virtuoso software [4], a computer-aided design (CAD) tool and simulation software. Table 2 summarizes the differential active balun parameters.

Table 2. Differential active balun parameter values and expressions

Parameters	Value
Input bias voltage	0.8V
Output DC voltage for maximum swing	0.7V (RFout1), 0.7V (RFout2)
Input impedance	∞
Output impedance, with resistor and capacitor loads	R1 || 1/*s*C1 (RFout1), R2 || 1/*s*C2 (RFout2)
Voltage gain, simplified (*s* = 0)	$\frac{g_{m2} \cdot G_{m1} R1}{G_{m1} + G_{m2} + \frac{1}{R_{tail}}}$ (RFout1) $-\frac{(g_{m2} \cdot G_{m1} R2) + \left(g_{m2} \cdot \frac{R2}{R_{tail}}\right)}{G_{m1} + G_{m2} + \frac{1}{R_{tail}}}$ (RFout2)
Noise Figure	$10log\left[1 + \frac{1 + \gamma(g_{m1} + g_{mb1})R1}{C1 \cdot k_B T \Delta f \cdot A_{v1}}\right]$ (RFout1) $10log\left[1 + \frac{1 + \gamma(g_{m2} + g_{mb2})R2}{C2 \cdot k_B T \Delta f \cdot A_{v2}}\right]$ (RFout2)

3. RESULTS AND DISCUSSION

The differential active balun is characterized and designed to achieve the target specifications. The extraction of all device parameters for use in simulations is done using Synopys Star-RCXT [5]. Simulations of the extracted view are done using Cadence Design Systems software. The active balun is designed to operate at 5.8GHz, which is a typical frequency for WiMAX applications. Measurements in the simulation plots are taken at 5.8GHz.

3.1 Gain and Gain Difference

There are many types of power gain defined for an amplifier. The most commonly specified and often the most useful is the transducer gain, G_T. It is defined as the ratio of the power delivered to the load to the power available from the source. Gain difference or gain error is the difference of the gains from the two output nodes of the active balun, and is considered as one of the most important parameters of the active balun design. Ideally, the gain difference of an active balun should be zero in magnitude. The responses in Fig. 4 and Fig. 5 for the gain and gain difference, respectively, are determined using AC analysis. Ideal voltage source is used with input bias voltage VIN set to 0.8V. All transistors M1, M2, and M3 are carefully derived and designed to satisfy the saturation region condition, with all $V_{DS,Q}$ at around 0.3V.

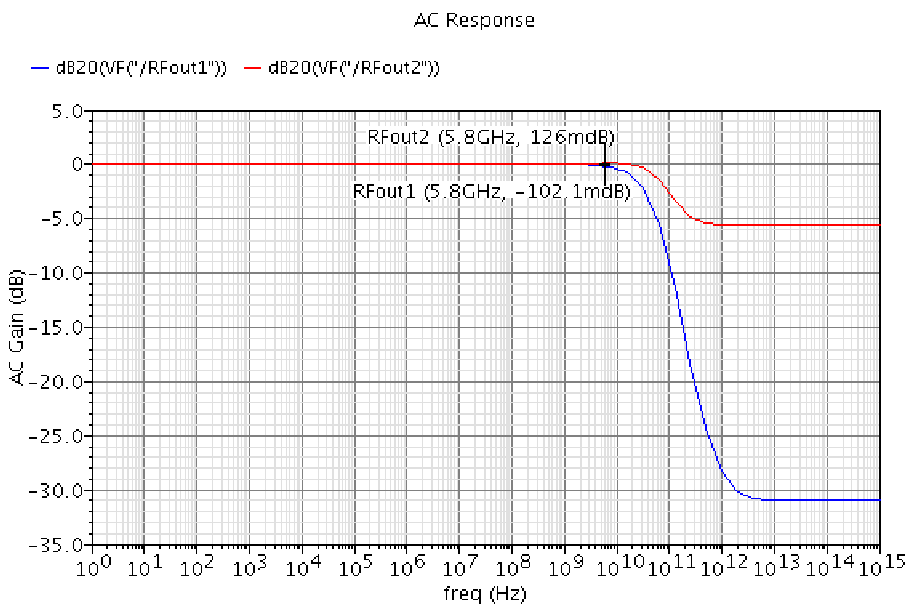

Fig. 4. AC analysis, gain plot

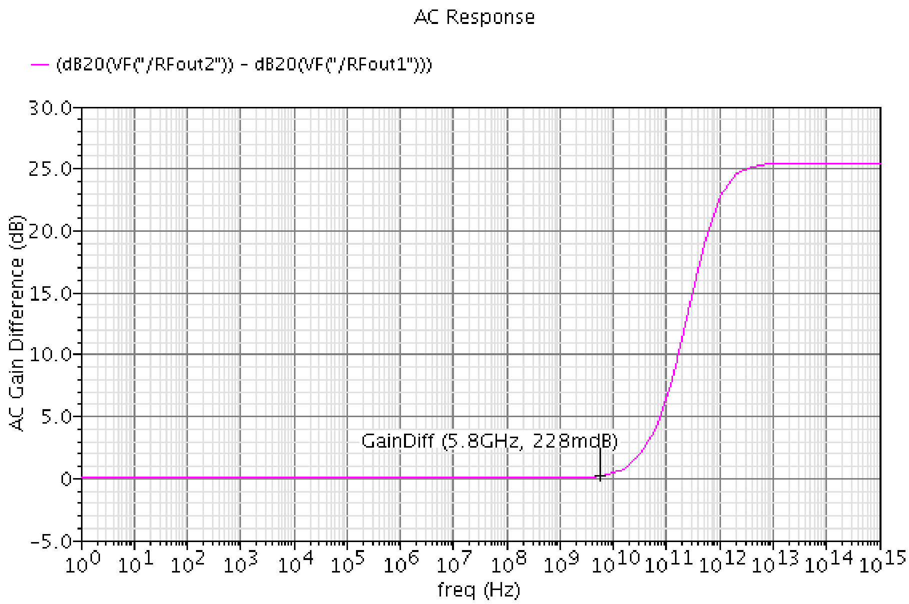

Fig. 5. AC analysis, gain difference plot

Differential active balun is designed to achieve a gain a little over 0dB. This is shown in the AC gain result in Fig. 4. Gain difference at 5.8GHz is at 0.228dB, which is still close to zero as expected since the gain response for the two outputs is very close to each other. The active balun is designed using ideal voltage source and with relatively high resistor loads at 250Ω and 178Ω to satisfy the needed gain.

3.2 Phase and Phase Difference

Another important parameter of an active balun is the phase difference. Phase difference is the difference between the phase of the non-inverting output node and the phase of inverting output node of the active balun. Figs. 6 and 7 show the AC analysis phase and phase difference responses, with ideal input voltage source.

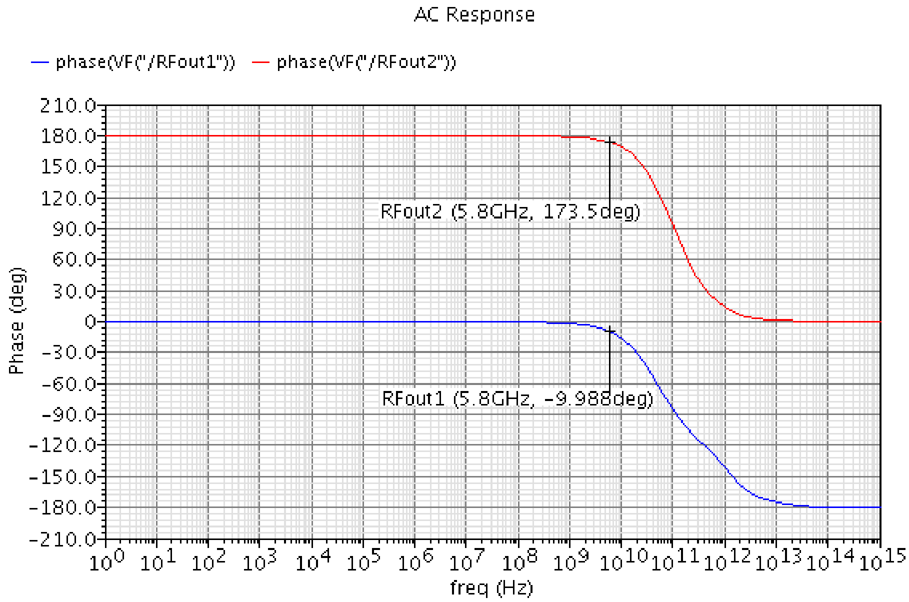

Fig. 6. AC analysis, phase plot

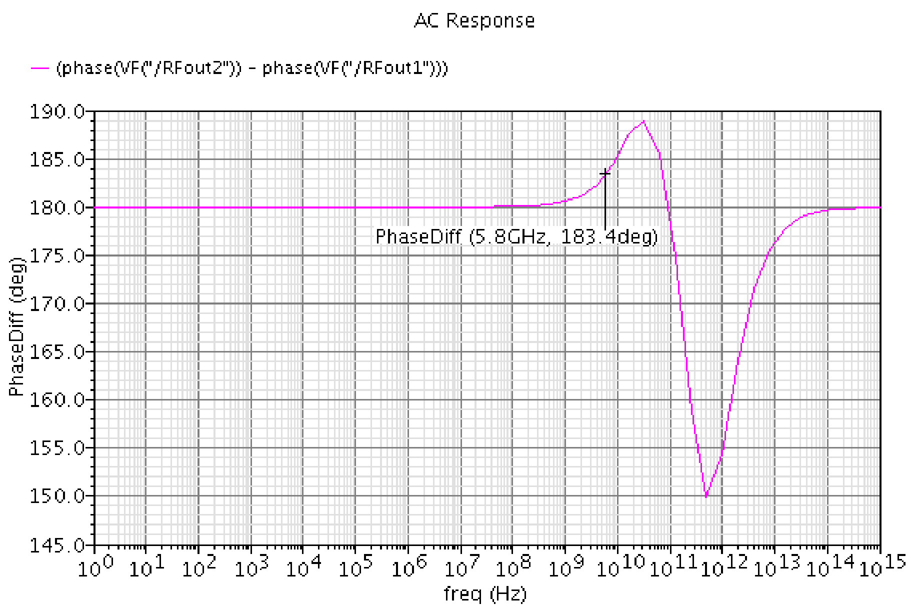

Fig. 7. AC analysis, phase difference plot

The results are within the target specification for the phase difference. AC analysis measurement for phase difference is at 183.4°.

3.3 Noise Figure

Noise performance is an important design consideration since it determines the susceptibility of the active balun to unwanted signal or noise. One important design parameters is the noise figure (NF), which is a measure of the amount of signal-to-noise-ratio degradation introduced by the circuit as seen at the output. Fig. 8 shows the noise figure result using PSS+PNoise analysis.

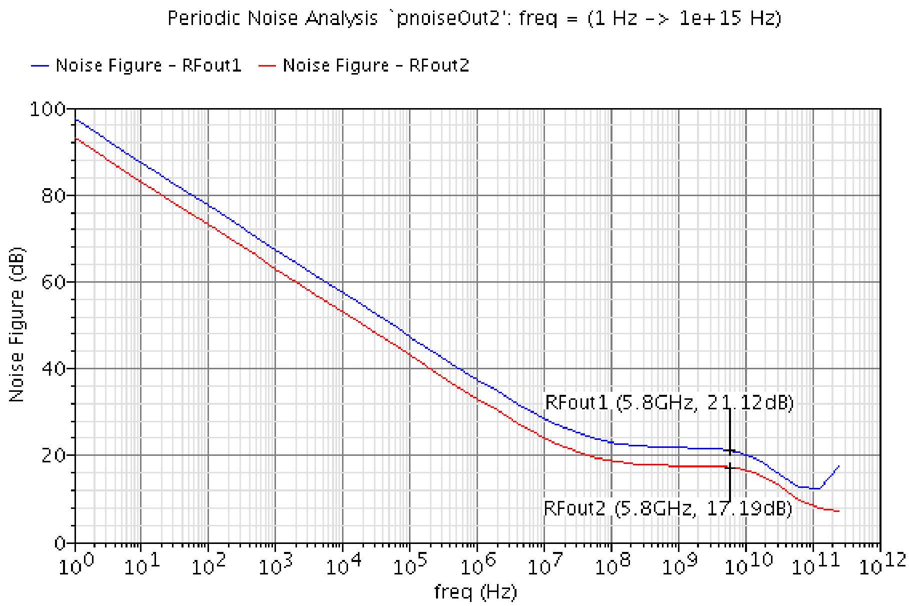

Fig. 8. Noise figure plot

Noise figure of 21.12dB and 17.19dB for RFout1 and RFout2 with respect to RFin are generated using PSS+PNoise analysis with RF input power set to -20dBm. High noise figures are generated since very low output signals are produced due to affected output load setting. With output matching network introduced, noise figures were improved to 8.973dB and 9.781dB, respectively for the two outputs.

3.4 Results Summary

Table 3 summarizes the performance of the three active balun designs.

Table 3. Performance summary of differential active balun

Parameters	Value	Target
Process/Technology	90nm CMOS	90nm CMOS
Supply voltage	1V	1V
Frequency	5.8GHz	5.8GHz
Gain difference	0.228dB	< 1dB
Phase difference	183.4°	180° ± 10°
Noise figure	8.973dB (RFout1), 9.781dB (RFout2)	< 10dB
Power consumption	3.599mW	< 10mW

The differential active balun design achieved a gain difference better than 1dB and a phase difference of 180°±10° or better at frequency of 5.8GHz. The balun is affected with the input and output loading since the circuit is designed with ideal input voltage source and no termination ports included. Low power consumption of at most 3.6mW is achieved, comparable to other low power designs in the past researches.

4. CONCLUSION AND RECOMMENDATIONS

A differential active balun is designed and implemented in a standard 90nm CMOS process, and carefully designed to satisfy the WiMAX receiver requirement at 5.8GHz. Simulation measurements are taken for parameters such as gain, phase, gain difference, phase difference, and noise figure.

The design achieved gain difference of less than 0.23dB and phase difference of 180° ± 3.4°. Noise figure performance is at around 8.97–9.78dB, comparable to previous designs and researches. Low power consumption of at most 3.6mW is achieved, comparable to other low power designs.

Future work could include designing active balun with high gain. Although it will sacrifice the bandwidth, it can still be realized at lower frequencies for practical applications. One possible work would be to integrate the active balun functionality on the circuit design of a differential circuit like that of the double-balanced mixer or differential LNA.

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