Original Research Article

Design of Common-Source/Drain Active Balun Using 90nm CMOS Technology

ABSTRACT

This research paper presents a design and study of a common-source/drain active balun circuit implemented in a standard 90-nm complementary metal-oxide semiconductor (CMOS) technology. The active balun desigan is intended for worldwide interoperability for microwave access (WiMAX) application, with operating frequency of 5.8GHz and supply voltage of 1V. Measurements are taken for parameters namely gain difference, phase difference, and noise figure. The common-source active balun design achieved a minimal gain difference of 0.016dB, phase difference of 180° ± 7.1°, and noise figure of 7.42-9.85dB, which are comparable to past active balun designs and researches. The design eventually achieved a low power consumption of 2.56mW.

Keywords: Common-source/drain active balun; 90nm CMOS; balun; gain; gain difference, phase difference, noise figure; WiMAX

1. INTRODUCTION

A considerable growth of interest in technologies that could deliver higher data rates over wider coverage led to the evolution of new wireless standards such as the IEEE 802.16-based WiMAX or the worldwide interoperability for microwave access. Like WiMAX, other communication systems namely Bluetooth, Wireless Fidelity (WiFi), and Long-Term Evolution (LTE) have the radio frequency (RF) receiver front-end that proves to be a critical part in the wireless system.. A typical wireless receiver is represented in Fig. 1 diagram.

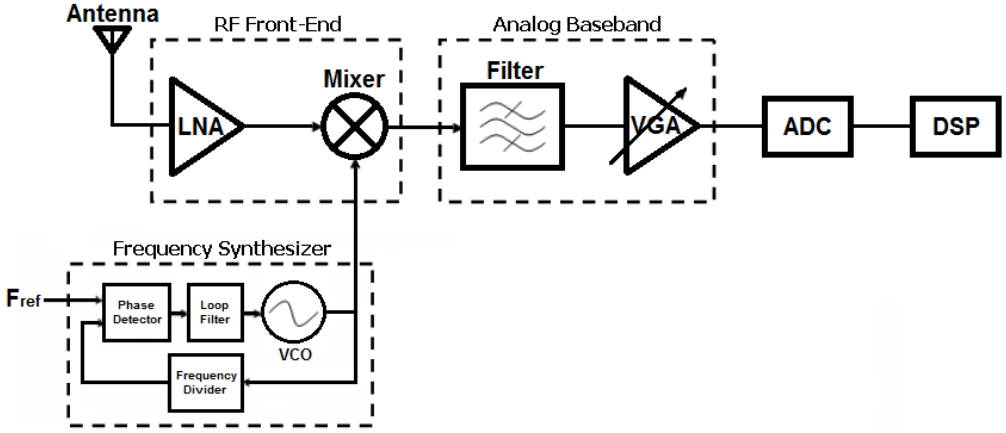

Fig. 1. Block diagram of a wireless receiver

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 [2-3].

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 in Fig. 2. Fig. 3 illustrates 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. Finally, 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.

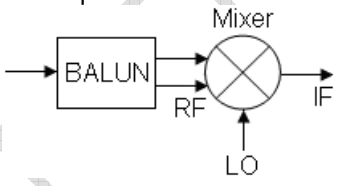

Fig. 2. Active balun supplying a differential mixer

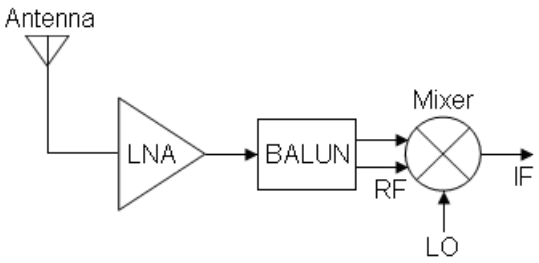

Fig. 3. Active balun as intermediate block between LNA and mixer

2. ACTIVE BALUN DESIGN

In this research paper, a common-source/drain active balun is designed and implemented in a standard 90nm complementary metal-oxide semiconductor (CMOS) technology. The supply voltage (VDD) 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 [4].

Table 1. Target specifications for the common-source/drain active balun design

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

Two 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. Another important parameter is the noise figure (NF), which is the measure of the amount signal-to-noise-ratio (SNR) degradation introduced by the circuit as seen in the output.

The common-source/drain active balun shown in Fig. 4 is composed of a single transistor M1. The input signal is fed into the gate of the transistor. Normal operation results in an inverted output signal at RFout2 and a non-inverted signal at RFout1. Ideally, these two outputs would have the same amplitude with a phase difference of 180º. Load resistors R1 and R2 determine the output voltages as well as the voltage gains of the two output signals with respect to the input signal.

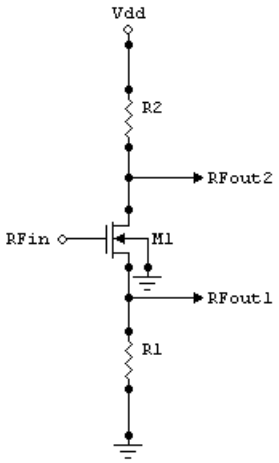

Fig. 4. Common-source/drain active balun schematic

Common-source topology exhibits a relatively high input impedance while providing voltage gain and requiring a minimal voltage headroom. Common-drain topology or source-follower, on the other hand, is occasionally employed as level shifters or buffers, impacting the overall frequency response. It also exhibits high input impedance. With the two topologies merged to function as an active balun, common-drain will dominate the response on the overall

voltage gain or attenuation because of the feedback effect of load resistor R1 with respect to the input.

Common-source/drain active balun is ideal for low voltage, low power WiMAX application due to low number of stacked devices. The active balun cannot actually produce gain in RFout1 due to its source-follower configuration. Since the two outputs should have balanced gain or attenuation, RFout2 should adjust and thus cannot produce gain. Hence, one important goal for this active balun design is to minimize the attenuation in outputs RFout1 and RFout2 and should be balanced with respect to the input RFin.

Drain current I_{DS} of transistor M1 is also the total supply current that is derived from the total power consumption of the active balun. With supply voltage V_{DD} = 1V, I_{DS} could be computed in Eq. (1) in terms of the output DC or bias voltages V1 (or V_{RFout1}) and V2 (or V_{RFout1}) and the output loads R1 and R2.

$$I_{DS} = \frac{V1 - 0}{R1} = \frac{V_{DD} - V2}{R2} \quad \rightarrow \quad I_{DS} = \frac{V1}{R1} = \frac{1V - V2}{R2} \qquad \text{Eq. (1)}$$

Assuming output loads R1 and R2 are equal to achieve a balanced response for V1 and V2 in terms of output swing, Eq. (1) would become Eq. (2).

$$V1 = 1V - V2 \qquad \text{Eq. (2)}$$

From the expression in Eq. (1), increasing I_{DS} increases the output voltage V1, while output voltage V2 decreases with I_{DS}. To achieve the minimum attenuation, V1 and V2 should take into account the drain-to-source voltage V_{DS} of transistor M1. This will also maximize the output swing in RFout1 and RFout2. Ensuring that transistor M1 operates at saturation region, V_{DS} should be at least V_{DSAT} or the overdrive voltage V_{OV}. With supply voltage V_{DD} = 1V, overdrive voltage V_{OV} set to 200mV and with the two outputs balanced, output voltage swings are computed as

$$V_{DS} = V2 - V1 \geq V_{DSAT} \quad \rightarrow \quad V2 - V1 \geq 0.2V \qquad \text{Eq. (3)}$$

Substituting V1 expression in Eq. (2) into Eq. (3),

$$V2 - (1V - V2) \geq 0.2V \qquad \text{Eq. (4)}$$

$$V2 \geq 0.6V \quad \rightarrow \quad 1V > V2 \geq 0.6V \qquad \text{Eq. (5)}$$

Output DC voltage V2 is computed to swing from 0.6V to 1V. Calculating for the output swing for V1,

$$V2 - V1 = V_{DS,Q} \geq 0.2V \quad \rightarrow \quad V1 \leq V2 - 0.2V \qquad \text{Eq. (6)}$$

$$V1 \leq 0.6V - 0.2V \qquad \text{Eq. (7)}$$

$$V1 \leq 0.4V \quad \rightarrow \quad 0.4V \geq V1 > 0 \qquad \text{Eq. (8)}$$

Output DC voltage swing for V1 is calculated to range from 0V to 0.4V. As previously mentioned, V1 increases with IDS while V2 decreases with I_{DS}. To maximize the output swing in RFout1 and RFout2, output DC voltages V1 and V2 should have values median to their output range in Eq. (8) and Eq. (5), respectively. This would also safeguard transistor M1 to operate at saturation region with V_{DS} of at least 200mV, while varying I_{DS}. The optimized values for output DC voltages V1 and V2 are given as

$$V1 = 0.2V \qquad \text{Eq. (9)}$$

$$V2 = 0.8V \quad \text{Eq. (10)}$$

With threshold voltage V_t set to 400mV, VOV set to 200mV, V1 set to 0.2V, and VDS ≥ V_{DSAT} = V_{OV}, input bias voltage could be determined in Eq. (11) to (12).

$$V_{DS} = V_{GS} - V_t \geq V_{DSAT} \quad \rightarrow \quad (V_{IN} - 0.2V) - 0.4V = 0.2V \quad \text{Eq. (11)}$$

$$V_{IN} = 0.8V \quad \text{Eq. (12)}$$

With input DC voltage V_{IN} set to 0.8V, it could swing from maximum 1V to 0.6V. Maximum input voltage is set to align with the supply voltage V_{DD} which is at 1V. Drain current I_{DS} of transistor M1 is also the total current that is derived from the total power consumption of the active balun. Using the square-law equation in Eq. (13), transconductance g_m could be computed in Eq. (14) to (15).

$$I_D = \frac{\mu C_{ox}}{2}\frac{W}{L}(V_{GS} - V_t)^2(1 + \lambda V_{DS}) \quad \text{Eq. (13)}$$

$$g_m = \frac{\delta I_{DS}}{\delta V_{GS}} = \mu C_{ox}\frac{W}{L}(V_{GS} - V_t)(1 + \lambda V_{DS}) \quad \text{Eq. (14)}$$

$$g_m = \mu C_{ox}\frac{W}{L}(V_{IN} - V_t - V1)(1 + \lambda V_{DS}) \quad \text{Eq. (15)}$$

Substituting I_{DS} from Eq. (13) into g_m in Eq. (14), an important design parameter could be determined, which is the gmoverId.

$$g_m = \frac{\delta I_{DS}}{\delta V_{GS}} = \frac{2I_{DS}}{(V_{GS} - V_t)} = \frac{2I_{DS}}{V_{OV}} = \frac{2I_{DS}}{V^*} = \frac{2I_{DS}}{(V_{IN} - V1 - V_t)} \quad \text{Eq. (16)}$$

$$\frac{g_m}{I_{DS}} = gmoverId = \frac{2}{(V_{IN} - V_t - I_{DS}R1)} \quad \text{Eq. (17)}$$

Proper DC input bias should be observed to realize good efficiency in terms of gmoverId. It can also be observed that the gmoverId is affected by the load resistance R1. For low power design, higher gmoverId is recommended [5]. As initially assumed, VOV is set 200mV for minimum attenuation and/or maximum voltage swing in outputs RFout1 and RFout2 with respect to the input RFin. With this, gmoverId could be estimated in Eq. (18).

$$\frac{g_m}{I_{DS}} = \frac{2}{200mV} = 10V^{-1} \quad \text{Eq. (18)}$$

It can be noted that to maintain the efficiency for low power consumption, lowering I_{DS} would also mean lowering gm. Transistor sizing depends on the target power consumption and likewise I_{DS}, thus, affecting g_m. Transconductance g_m is a key parameter that determines the voltage gain of the active balun, which will be discussed in the succeeding section.

Resistors R1 and R2 could be determined given the setup for minimum attenuation and maximum voltage swing in the two outputs.

$$R1 = \frac{V1}{I_{DS}} = \frac{0.2V}{I_{DS}} \quad R2 = \frac{V_{DD} - V2}{I_{DS}} = \frac{0.2V}{I_{DS}} \quad \text{Eq. (19)}$$

To have a balanced attenuation in the two outputs, R1 should be equal to R2. With V1 and V2 set to the optimum value and V_{DD} set to 1V, decreasing the supply current (which is equal to I_{DS}) would increase the value of R1 and R2. Large resistor values contribute to more noise and parasitics. Since the active balun is targeted for low power consumption, tradeoff between drain current I_{DS} and resistor values is inevitable. Moreover, the design is optimized to meet the target performance specifications suitable for WIMAX receiver. The active balun design is implemented in a standard 90nm CMOS process using Cadence Virtuoso software [6], a computer-aided design (CAD) tool and simulation software. Table 2 summarizes the common-source/drain active balun parameters.

Table 2. Common-source/drain active balun parameters expressions

Parameters	Value
Input bias voltage	0.8V
Output DC voltage for maximum swing	0.2V (RFout1), 0.8V (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)	$\frac{g_m R1}{1+(g_m+g_{mb})R1}$ (RFout1)
	$\frac{-g_m R2}{1+(g_m+g_{mb})R1}$ (RFout2)
Output noise voltage	$\frac{k_B T}{C1}[1+\gamma(g_m+g_{mb})R1]$ (RFout1)
	$\frac{k_B T}{C2}[1+\gamma(g_m+g_{mb})R2]$ (RFout2)
Noise Figure	$10log\left[1+\frac{1+\gamma(g_m+g_{mb})R1}{C1\cdot k_B T\Delta f\cdot A_{v1}}\right]$ (RFout1)
	$10log\left[1+\frac{1+\gamma(g_m+g_{mb})R2}{C2\cdot k_B T\Delta f\cdot A_{v2}}\right]$ (RFout2)

3. RESULTS AND DISCUSSION

The common-source/drain active balun is characterized and designed to achieve the target specifications. The extraction of all device parameters for use in simulations is done using Synopsys Star-RCXT [7]. 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. 5 and Fig. 6 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. Drain-to-source voltage, VDS,Q = V2 – V1, was measured at 528.6mV with VGS – Vt = 71.6mV, confirming the transistor M1 operating at saturation. Fig. 5 shows the response using AC analysis.

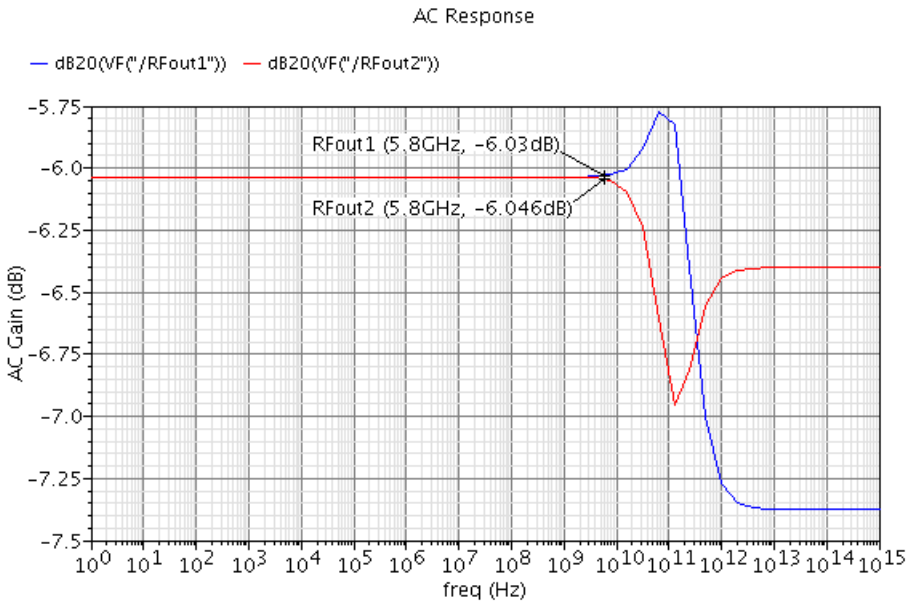

Fig. 5. AC analysis, gain plot

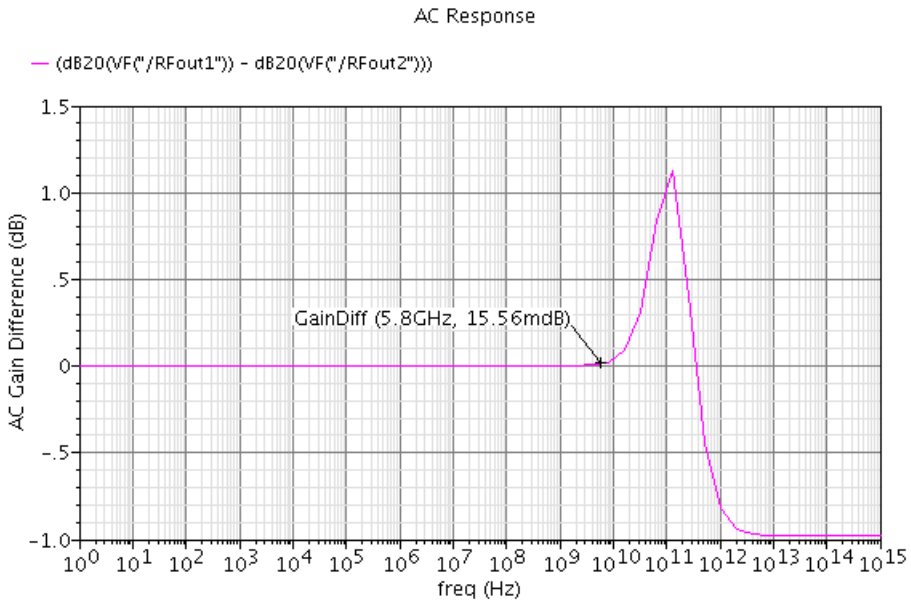

Fig. 6. AC analysis, gain difference plot

Since the active balun has the configuration of common-drain, it is expected that the gains would fall below the target of at least 0dB. AC gains are at around -6dB. Take note that the three active baluns are designed with ideal voltage source at the input, thus with very high (if not infinite) input impedance, and the output is left with no termination. Since the resistor loads of the active balun are of the same value, gain difference was maintained very low at 0.015dB.

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. 7 and 8 show the AC analysis phase and phase difference responses, with ideal input voltage source.

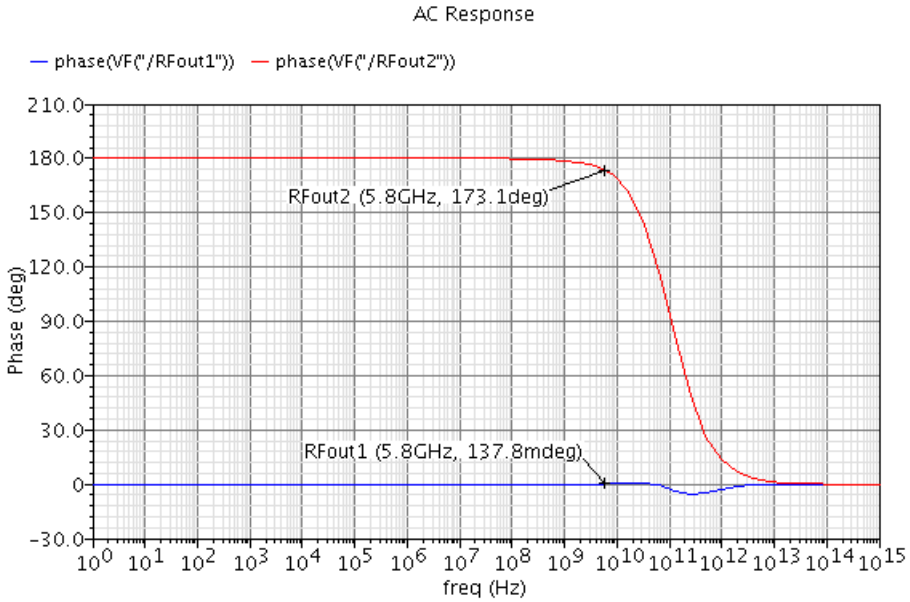

Fig. 7. AC analysis, phase plot

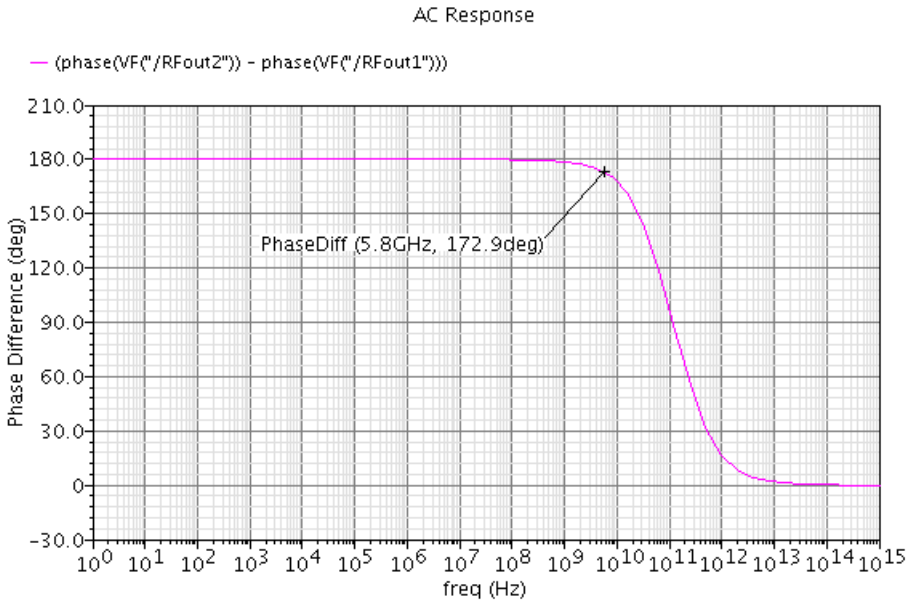

Fig. 8. AC analysis, phase difference plot

Same analysis with the gain and gain difference are done with the phase and phase difference. The results are within the acceptable values especially for the target phase difference with measurement at 172.9°.

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. 9 shows the noise figure result using PSS+PNoise analysis.

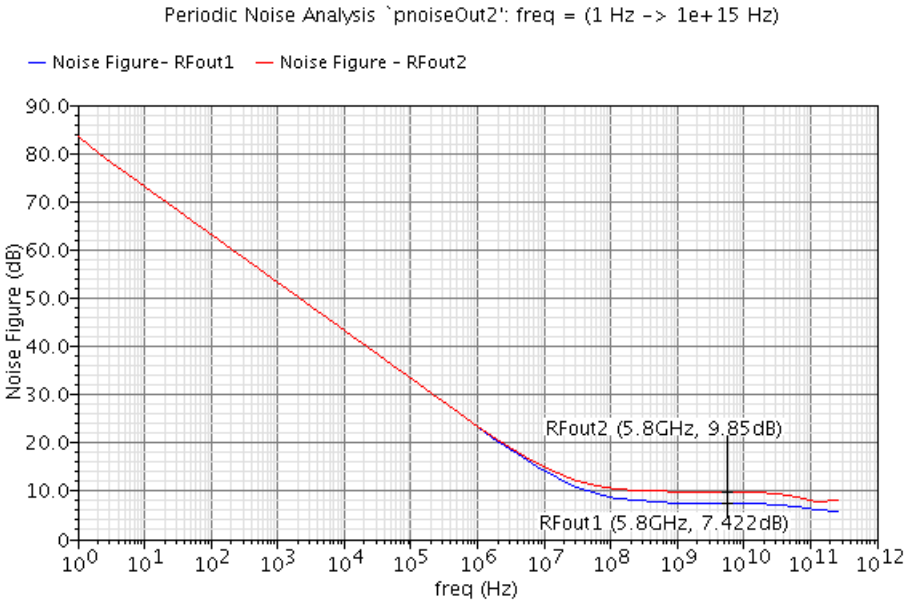

Fig. 9. Noise figure plot

Noise figure of 7.422dB and 9.85dB for RFout1 and RFout2 with respect to RFin are generated using PSS+PNoise analysis with RF input power set to -20dBm. It is worth noting that the noise figure from PNoise analysis is slightly higher than the noise figure generated from SP analysis because at prf = -20dBm the active balun demonstrated very weak nonlinearity and noise as other high harmonics are convoluted.

3.4 Results Summary

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

Table 3. Performance summary of differential active balun

Parameters	Target	Value
Process/Technology	90nm CMOS	90nm CMOS
Supply voltage	1V	1V
Frequency	5.8GHz	5.8GHz
Gain difference	< 1dB	0.016dB
Phase difference	180° ± 10°	172.9°
Noise figure	< 10dB	7.422dB (RFout1), 9.850dB (RFout2)
Power consumption	< 10mW	2.558mW

The common-source/drain 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 2.56mW is achieved, comparable to other low power designs in the past researches.

4. CONCLUSION AND RECOMMENDATIONS

A common-source/drain 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 0.02dB and phase difference of 180° ± 7.1°. Noise figure performance is at around 7.42–9.85dB, comparable to previous designs and researches. Low power consumption of at most 2.56mW 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.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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