

Differential Active Balun Design for WiMAX Applications

Frederick Ray I. Gomez^{1,2*}, John Richard E. Hizon¹,
Maria Theresa G. De Leon¹

¹University of the Philippines, Diliman, Quezon City, Philippines 1101

²STMicroelectronics, Inc., Calamba City, Laguna, Philippines 4027

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 $180^\circ \pm 3.4^\circ$, 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 [1-2] such as bluetooth, wireless fidelity (WiFi), and worldwide interoperability for microwave access (WiMAX). A typical receiver is illustrated in Fig. 1 block diagram.

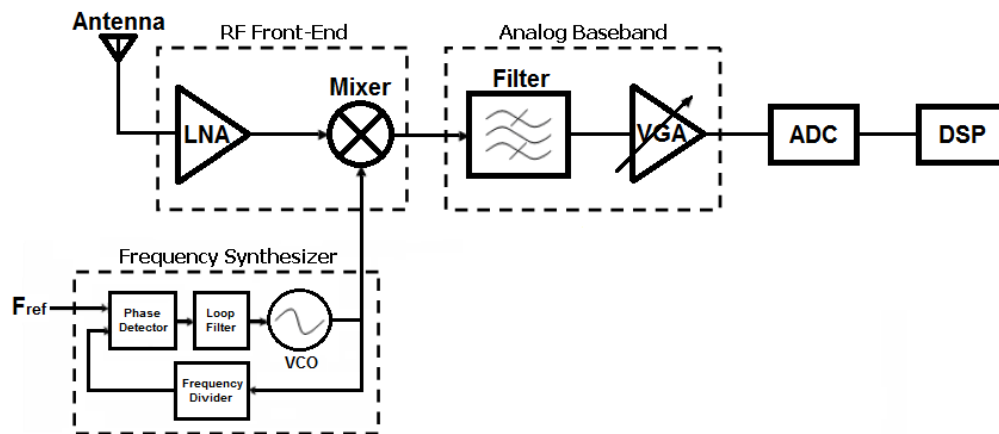


Fig. 1. Block diagram of a wireless receiver [12]

* Tel.: +63 2 792 5665

E-mail address: frederick-ray.gomez@st.com, f.i.gomez@ieee.org

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 [2-3]. 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 [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) [4]. It can also be used to supply differential signal to a mixer [5]. 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.

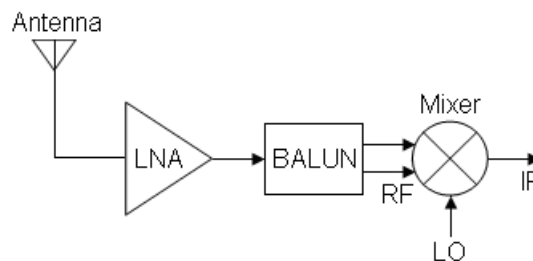


Fig. 2. Active balun as intermediate block between LNA and mixer [12]

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 [5-8] and from the summary of parameters as per WiMAX standard [9].

Table 1. Minimum target parameter values for the differential active balun design [12]

Parameters	Value
Frequency	5.8GHz
Gain difference	< 1dB
Phase difference	$180^\circ \pm 10^\circ$
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.

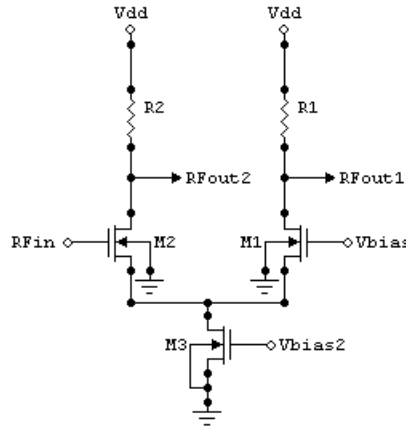


Fig. 3. Schematic diagram of differential active balun [12]

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_{DS3} . 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).

$$V_{DD} > V_1 \geq V_{DSAT1} + V_{DSAT3} \rightarrow 1V > V_1 \geq 0.4V \quad \text{Eq. (1)}$$

$$V_1 = V_{RFout1} = \frac{V_{DD} + V_{OV1} + V_{OV3}}{2} = \frac{1V + 0.4V}{2} = 0.7V \quad \text{Eq. (2)}$$

$$V_{DD} > V_2 \geq V_{DSAT2} + V_{DSAT3} \rightarrow 1V > V_2 \geq 0.4V \quad \text{Eq. (3)}$$

$$V_2 = V_{RFout2} = \frac{V_{DD} + V_{OV2} + V_{OV3}}{2} = \frac{1V + 0.4V}{2} = 0.7V \quad \text{Eq. (4)}$$

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. The active balun circuit is implemented in a standard 90nm CMOS process using Cadence Virtuoso software [10], 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	$R1 \parallel 1/sC1$ (RFout1), $R2 \parallel 1/sC2$ (RFout2)
	$\frac{g_{m2} \cdot G_{m1} R1}{G_{m1} + G_{m2} + \frac{1}{R_{out}}} \quad (\text{RFout1})$
Voltage gain, simplified ($s = 0$)	$-\frac{(g_{m2} \cdot G_{m1} R2) + (g_{m2} \cdot \frac{R2}{R_{out}})}{G_{m1} + G_{m2} + \frac{1}{R_{out}}} \quad (\text{RFout2})$
	$10 \log \left[1 + \frac{1 + r(g_{m1} + g_{m2})R1}{C1 \cdot k_B T \Delta f \cdot A_{v1}} \right] \quad (\text{RFout1})$
Noise Figure	$10 \log \left[1 + \frac{1 + r(g_{m2} + g_{m1})R2}{C2 \cdot k_B T \Delta f \cdot A_{v2}} \right] \quad (\text{RFout2})$

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 Synopsys Star-RCXT [11]. 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.

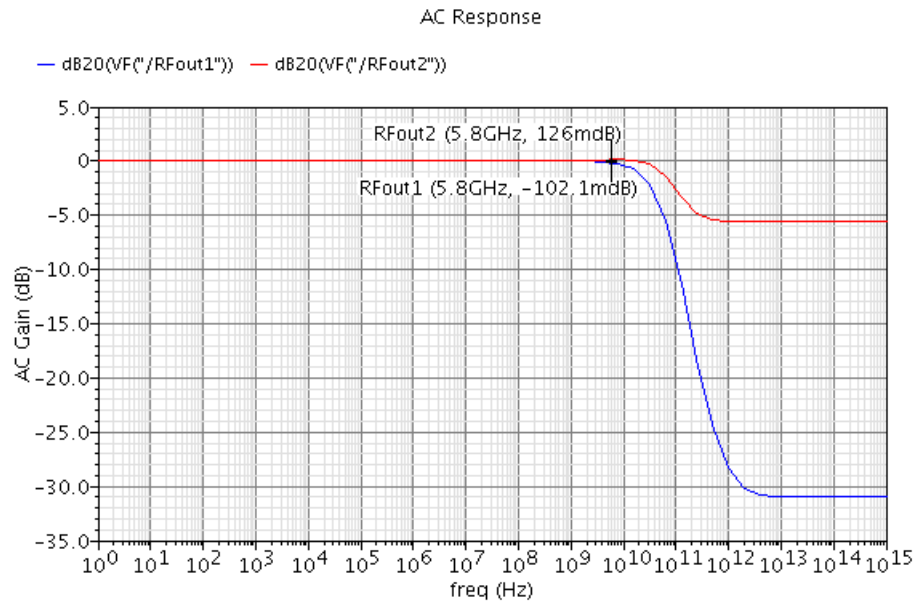
* Tel.: +63 2 792 5665

E-mail address: frederick-ray.gomez@st.com, f.i.gomez@ieee.org

3.1 Gain and Gain Difference

128

129 There are many types of power gain defined for an amplifier. The most commonly specified
 130 and often the most useful is the transducer gain, G_T . It is defined as the ratio of the power
 131 delivered to the load to the power available from the source. Gain difference or gain error is
 132 the difference of the gains from the two output nodes of the active balun, and is considered
 133 as one of the most important parameters of the active balun design. Ideally, the gain
 134 difference of an active balun should be zero in magnitude. The responses in Fig. 4 and Fig.
 135 5 for the gain and gain difference, respectively, are determined using AC analysis. Ideal
 136 voltage source is used with input bias voltage V_{IN} set to 0.8V. All transistors M1, M2, and
 137 M3 are carefully derived and designed to satisfy the saturation region condition, with all $V_{DS,Q}$
 138 at around 0.3V [12].



139

140

141

142

Fig. 4. AC analysis, gain plot

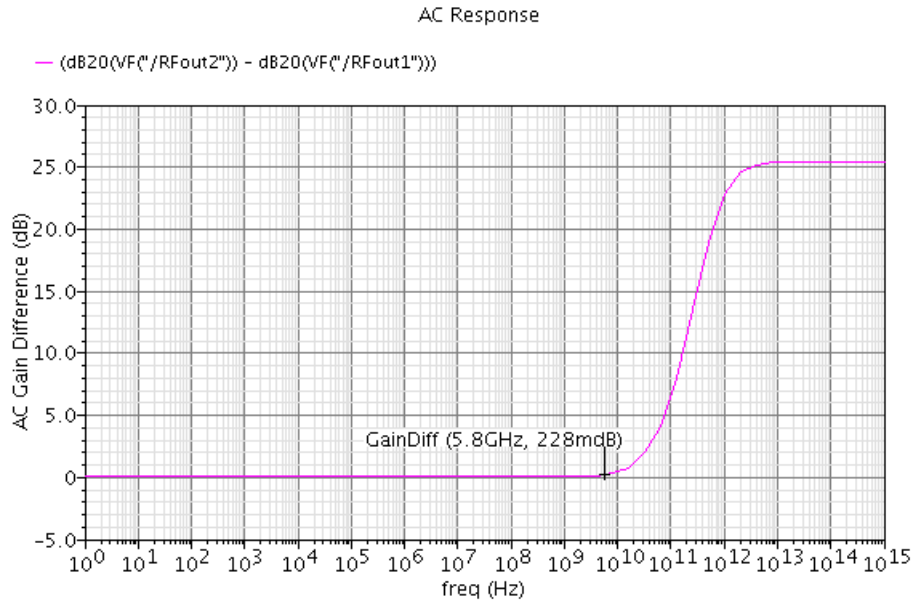


Fig. 5. AC analysis, gain difference plot

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.

159

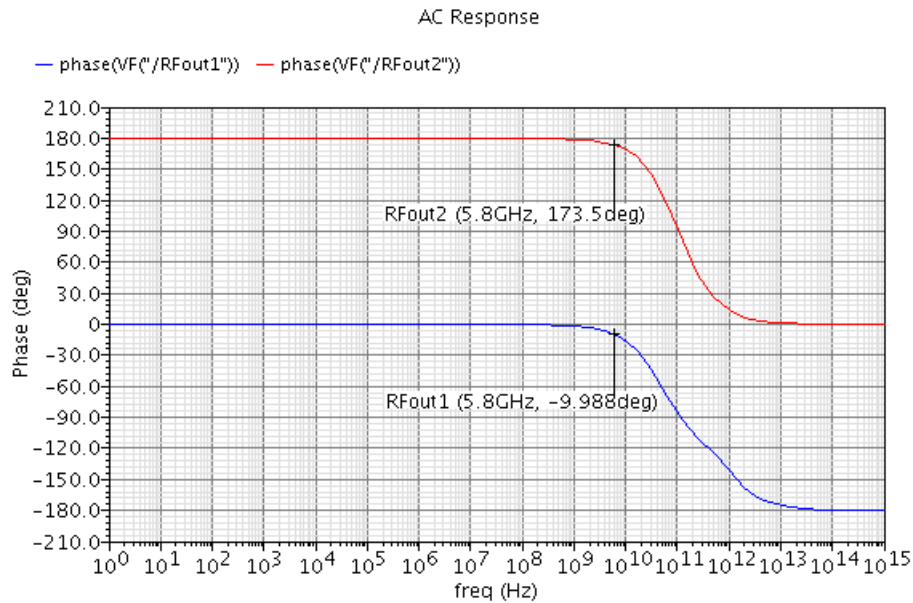


Fig. 6. AC analysis, phase plot

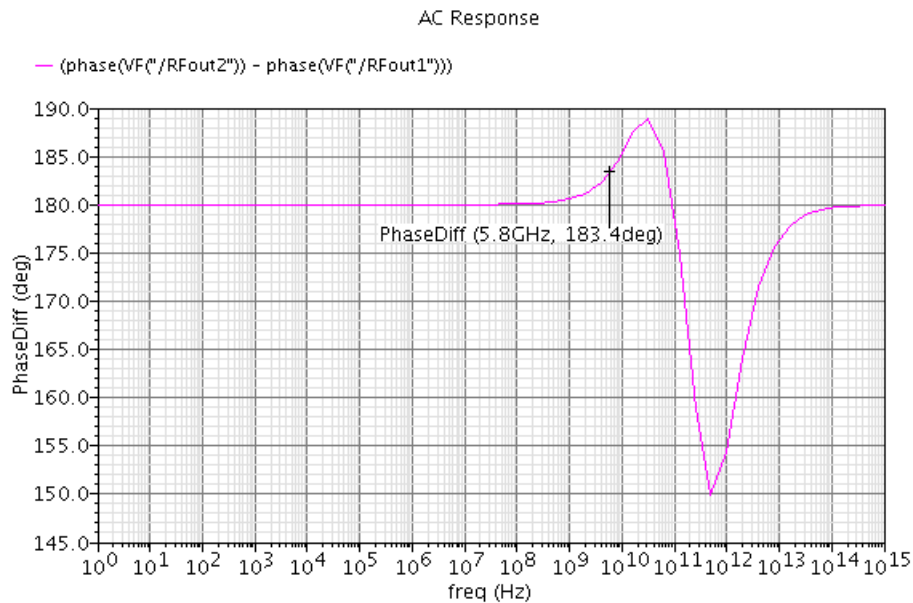


Fig. 7. AC analysis, phase difference plot

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

174 introduced by the circuit as seen at the output. Fig. 8 shows the noise figure result using
 175 PSS+PNoise analysis.
 176

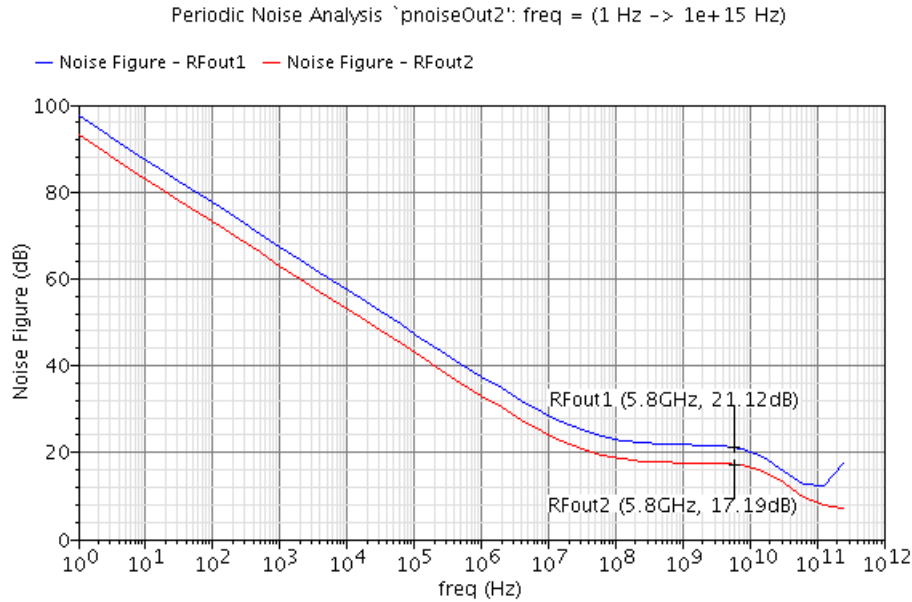


Fig. 8. Noise figure plot

177
 178
 179
 180 Noise figure of 21.12dB and 17.19dB for RfOut1 and RfOut2 with respect to RFin are
 181 generated using PSS+PNoise analysis with RF input power set to -20dBm. High noise
 182 figures are generated since very low output signals are produced due to affected output load
 183 setting. With output matching network introduced, noise figures were improved to 8.973dB
 184 and 9.781dB, respectively for the two outputs.
 185

186 3.4 Results Summary

187
 188 Table 3 summarizes the performance of the three active balun designs.
 189

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

192
 193 The differential active balun design achieved a gain difference better than 1dB and a phase
 194 difference of 180°±10° or better at frequency of 5.8GHz. The balun is affected with the input
 195 and output loading since the circuit is designed with ideal input voltage source and no

* Tel.: +63 2 792 5665

E-mail address: frederick-ray.gomez@st.com, f.i.gomez@ieee.org

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 $180^\circ \pm 3.4^\circ$. 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.

ACKNOWLEDGMENTS

The authors would like to thank the Department of Science and Technology (DOST), the Philippine Council for Advanced Science and Technology Research and Development under DOST (DOST-PCASTRD), and the Engineering Research and Development for Technology Consortium (DOST-ERDT) for the extensive support. The authors would like to express gratitude to the Microelectronics and Microprocessors Laboratory team of the University of the Philippines for the technical support during the course of the study. Author F.R. Gomez is greatly thankful to the STMicroelectronics Calamba Central Engineering and Development Team and the Management Team for the immeasurable support.

REFERENCES

1. Crols J, Donnay S, Steyaert M, Gielen G. A high-level design and optimization tool for analog RF receiver front-ends. International Computer-Aided Design Conference, pp. 550-553; November 1995.
2. Gomez FR, De Leon MT, Roque CR. Active balun circuits for WiMAX receiver front-end. TENCON 2010 – IEEE Region 10 Conference, pp. 1156-1161; November 2010.
3. Azevedo F, Fortes F, Rosario MJ. A new on-chip CMOS active balun integrated with LNA. 14th IEEE International Conference on Electronics, Circuits and Systems, pp. 1213–1216; December 2007.
4. Zhang HB, Cai M, Wu H, Chen HL. A 2.5GHz BiCMOS low noise and high-gain differential LNA for WLAN receiver. Asia Pacific Conference on Postgraduate Research in Microelectronics and Electronics, pp. 33-36; January 2009.
5. Hsu TT, Kuo CN. Low voltage 2-mW 6~10.6-GHz ultra-wideband CMOS mixer with active balun. IEEE International Symposium on Circuits and Systems, pp. 5704-5707; September 2006.
6. Ma H, Fang SJ, Lin F, Nakamura H. Novel active differential phase splitters in RFIC for wireless applications. IEEE Transactions on Microwave Theory and Techniques, vol. 46, pp. 2597-2603; December 1998.

* Tel.: +63 2 792 5665

E-mail address: frederick-ray.gomez@st.com, f.i.gomez@ieee.org

- 247 7. Do MA, Lim WM, Ma JG, Yeo KS. Design of a phase splitter for 3rd ISM band. IEEE
248 Conference on Electron Devices and Solid-State Circuits, pp. 237-240; December 2003.
249 8. Kawashima M, Nakagawa T, Araki K. A novel broadband active balun. 33rd European
250 Microwave Conference, vol. 2, pp. 495-498; October 2003.
251 9. IEEE standard 802.16e-2005. Part 16: Air interface for fixed and mobile broadband
252 wireless access systems, Amendment 2: Physical and medium access control layers for
253 combined fixed and mobile operation in licensed bands, and Corrigendum 1. IEEE
254 Computer Society and IEEE Microwave Theory and Techniques Society; 28 February
255 2006.
256 10. Cadence Design Systems, Inc. Custom IC / analog / RF design – circuit design.
257 [https://www.cadence.com/content/cadence-www/global/en_US/home/tools/custom-ic-](https://www.cadence.com/content/cadence-www/global/en_US/home/tools/custom-ic-analog-rf-design/circuit-design.html)
258 [analog-rf-design/circuit-design.html](https://www.cadence.com/content/cadence-www/global/en_US/home/tools/custom-ic-analog-rf-design/circuit-design.html)
259 11. Synopsys, Inc. StarRC – parasitic extraction. [https://www.synopsys.com/](https://www.synopsys.com/implementation-and-signoff/signoff/starrc.html)
260 [implementation-and-signoff/signoff /starrc.html](https://www.synopsys.com/implementation-and-signoff/signoff/starrc.html)
261 12. Frederick Ray I.G., John Richard E. Hizon and Maria Theresa G. De Leon. 2019. Design
262 and Simulation Study of Active Balun Circuits for WiMAX Applications, *Asian Journal of*
263 *Engineering and Technology*, 7(1), 1-10.