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CMOS differential active balun circuit small-signal analysis

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Abstract

The paper presents a study of a differential active balun circuit in terms of the small-signal analysis, implemented in a complementary metal-oxide semiconductor (CMOS) technology. It is important to analyze the small-signal or alternating current (AC) response or frequency response of the active balun to determine the maximum frequency of operation and the effective bandwidth of the designed circuit. This is to ensure that the designed active balun circuit would normally produce gain or attenuation at the desired frequency of operation. Eventually, design tradeoffs are inevitable and are carefully considered in the analysis and design.

Keywords: AC analysis, differential active balun, small-signal analysis, transconductance, voltage gain, CMOS

1. Introduction

A balun (balanced-unbalanced) 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. Furthermore, baluns are classified as either active or passive baluns depending on the electronic 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 [1-2]. One of the active balun topologies is the differential active balun circuit shown in Fig. 1, consist of 3 transistors namely M1 and M2 for the differential output, and M3 for the tail current, designed in complementary metal-oxide semiconductor (CMOS) technology. 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 difference. Remarkably, this active balun topology is capable of producing gain.

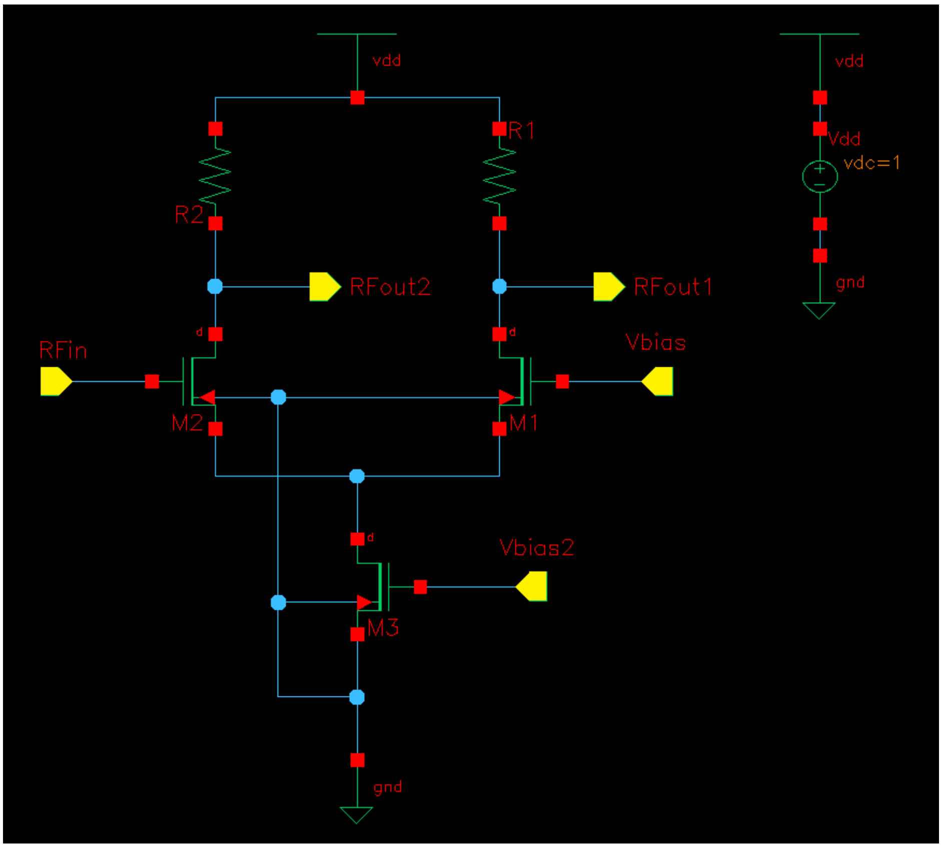

Fig 1: Differential active balun circuit schematic diagram.

2. Small-Signal Analysis

It is important to analyze the alternating current (AC) response or frequency response of the active balun to determine maximum frequency of operation and the effective bandwidth of the designed circuit. This is to ensure that the designed active balun would normally produce gain or attenuation at the desired frequency of operation, implemented in a CMOS technology. Fig. 2 shows the small-signal equivalent circuit of the differential active balun with tail resistor (R_{tail}) representing the output resistance of transistor M3. Output resistances r_{o1} and r_{o2} of transistors M1 and M2, respectively, are assumed to be very high and thus neglected. Inherent capacitances are identified in the model, with output load capacitances C1 and C2. Lastly, the circuit is driven by a finite source resistance (Rs).

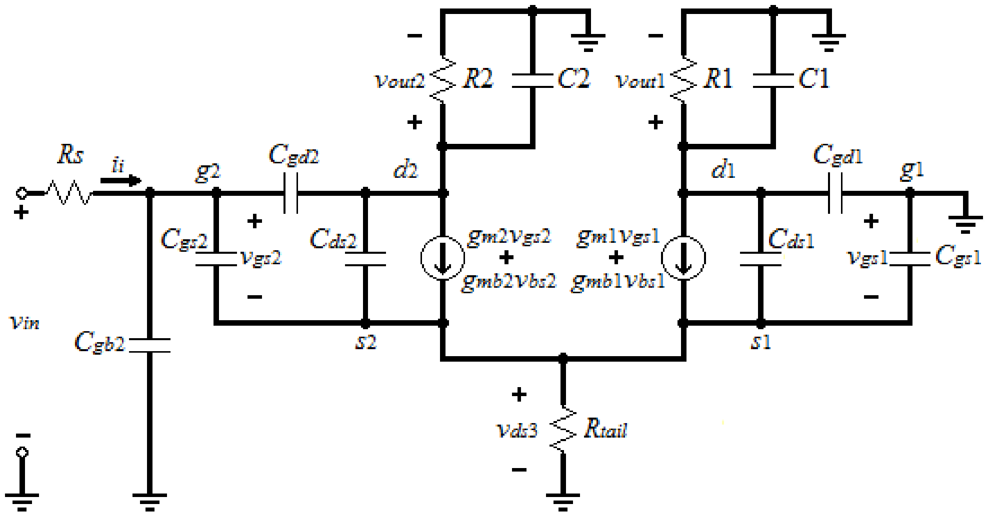

Fig 2: Differential active balun small-signal equivalent circuit.

Tail resistor (R_{tail}) effectively represents transistor M3 since current $g_{m3}*v_{gs3}$ equates to zero with v_{g3} and v_{s3} both connected to ground. Doing Kirchhoffs circuit law (KCL) on the drain node of M3 or source nodes of M1 and M2 results to the succeeding expressions. Normally, drain-to-source capacitances (C_{ds}) are relatively low, thus could be neglected. With $v_{s2} = v_{s1} = v_{ds3}$,

$$g_{m2}v_{gs2} + g_{mb2}v_{bs2} + \frac{v_{g2} - v_{ds3}}{1/sC_{gs2}} + g_{m1}v_{gs1} + g_{mb1}v_{bs1} + \frac{v_{g1} - v_{ds3}}{1/sC_{gs1}} = \frac{v_{ds3}}{R_{tail}} \tag{1}$$

$$v_{ds3} = \frac{v_{g2}\left(g_{m2} + sC_{gs2}\right)}{G_{mT} + \frac{1}{R_{tail}} + sC_{gsT}} \tag{2}$$

$$with \quad G_{mT} = G_{m1} + G_{m2} \quad and \quad C_{gsT} = C_{gs1} + C_{gs2} \tag{3}$$

A relationship between the input gate voltage (v_{g2}) and the M3 voltage drop v_{ds3} is now presented in the expression in (2). This expression is necessary for determining the expression for the input voltage and output voltages, as well as voltage gains A_{v1} and A_{v2} for the two outputs with respect to the input. With source resistance (Rs) set to zero, the voltage gain transfer functions are given as

$$A_{v1} = \frac{v_{out1}}{v_{in}}(s) = \frac{\dfrac{(g_{m2} + sC_{gs2})(g_{m1} + g_{mb1})R1}{G_{mT} + \frac{1}{R_{tail}} + sC_{gsT}}}{1 + s(C1 + C_{gd1})R1} \tag{4}$$

$$A_{v2} = \frac{v_{out2}}{v_{in}}(s) = -\frac{\left[\dfrac{g_{m2}\left(G_{m1} + \frac{1}{R_{tail}}\right) + g_{m2}sC_{gs1} - g_{mb2}sC_{gs2}}{G_{m1} + G_{m2} + \frac{1}{R_{tail}} + sC_{gs1} + sC_{gs2}} - sC_{gd2}\right]R2}{1 + s\left(C2 + C_{gd2}\right)R2} \tag{5}$$

where

$$G_{mT} = G_{m1} + G_{m2} \quad , \quad C_{gsT} = C_{gs1} + C_{gs2} \tag{6}$$

$$G_{m1} = g_{m1} + g_{mb1} \quad , \quad G_{m2} = g_{m2} + g_{mb2} \tag{7}$$

3. The corresponding pole locations could be estimated as

$$\omega_{p,v1} = \frac{1}{R1\left(C1 + C_{gd1}\right)} \tag{8}$$

$$\omega_{p,v2} = \frac{1}{R2\left(C2 + C_{gd2}\right)} \tag{9}$$

Letting s = 0, voltage gains A_{v1} and A_{v2} from (4) and (5), respectively, could be estimated. This neglects the effects of the capacitances in the circuit. Shown in Fig. 3 is the differential active balun small-signal simplified model. It is also noted that input of the active balun is connected to the gate of transistor M1, thus input resistance $R_i \rightarrow \infty$. Source resistance is also neglected in the model.

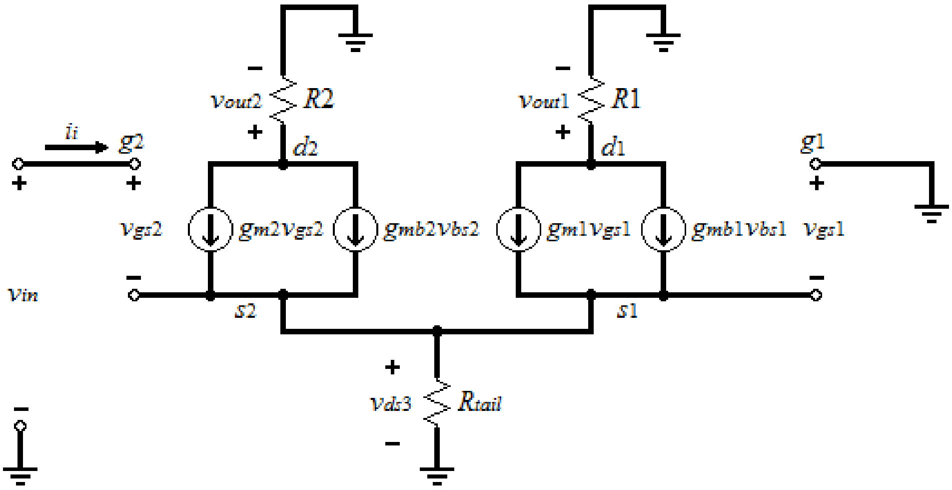

Fig 3: Differential active balun low frequency small-signal circuit.

Resistor R_{tail} effectively represents transistor M3 since current $g_{m3}{*}v_{gs3}$ equates to zero with v_{g3} and v_{s3} both connected to ground. Doing KCL on the drain node of M3 or source nodes of M1 and M2, results to the following expressions shown below.

$$g_{m2}v_{gs2} + g_{mb2}v_{bs2} + g_{m1}v_{gs1} + g_{mb1}v_{bs1} = \frac{v_{ds3}}{R_{tail}} \tag{10}$$

$$v_{ds3} = \frac{g_{m2} \cdot v_{in}}{G_{m1} + G_{m2} + \dfrac{1}{R_{tail}}} \tag{11}$$

$$with \quad G_{m1} = g_{m1} + g_{mb1} \quad and \quad G_{m2} = g_{m2} + g_{mb2} \tag{12}$$

A relationship between the input small signal (v_{in}) and the M3 voltage drop v_{ds3} is now presented in (11). The expression corresponds to the expression in (2) with frequency response not taken into effect. This equation is necessary to determine the voltage gains A_{v1} and A_{v2}.

$$A_{v1} = \frac{v_{out1}}{v_{in}} = \frac{g_{m2} \cdot G_{m1}R1}{G_{m1} + G_{m2} + \dfrac{1}{R_{tail}}} \tag{13}$$

$$A_{v2} = \frac{v_{out2}}{v_{in}} = -\frac{(g_{m2} \cdot G_{m1} R2) + \left(g_{m2} \cdot \frac{R2}{R_{tail}}\right)}{G_{m1} + G_{m2} + \frac{1}{R_{tail}}} \tag{14}$$

If the differential active balun is assumed to be balanced, that is with transconductance $G_{m1} = G_{m2}$, and with ideal tail current source such that $R_{tail} \rightarrow \infty$, voltage gains A_{v1} and A_{v2} could be simplified as

$$A_{v1} = \frac{v_{out1}}{v_{in}} = \frac{g_{m2} \cdot G_{m1} R1}{G_{m1} + G_{m1}} = \frac{g_{m2} R1}{2} \tag{15}$$

$$A_{v2} = \frac{v_{out2}}{v_{in}} = -\frac{g_{m2} \cdot G_{m1} R2 + 0}{G_{m1} + G_{m1}} = -\frac{g_{m2} R2}{2} \tag{16}$$

If load resistors R1 = R2, resulting voltage gains would also be equal. This is a characteristic of a balanced differential amplifier.

$$|A_{v1}| = |A_{v2}| = \frac{g_{m2} R1}{2} = \frac{g_{m2} R2}{2} \tag{17}$$

But then again, due to non-ideality, the output impedance of M3 is not as high as required resulting to unequal signal in the two output branches. As previously stated, one way to compensate for the imbalance is to adjust the value of load resistors R1 and R2. Expressions in (13) and (14) will then be the bases for the two voltage gains A_{v1} and A_{v2}, accordingly. Equating these two equations would result to the relationship of the load resistors with the transconductances and R_{tail}, as shown in the succeeding expressions.

$$|A_{v1}| = |A_{v2}| = \frac{g_{m2} \cdot G_{m1} R1}{G_{m1} + G_{m2} + \frac{1}{R_{tail}}} = \frac{(g_{m2} \cdot G_{m1} R2) + \left(g_{m2} \cdot \frac{R2}{R_{tail}}\right)}{G_{m1} + G_{m2} + \frac{1}{R_{tail}}} \tag{18}$$

$$G_{m1} R1 = \left(G_{m1} + \frac{1}{R_{tail}}\right) R2 \tag{19}$$

$$R1 = \left(1 + \frac{1}{G_{m1} R_{tail}}\right) R2 \tag{20}$$

$$R2 = \left(\frac{1}{1 + \frac{1}{G_{m1} R_{tail}}}\right) R1 \tag{21}$$

Where

$$G_{m1} = g_{m1} + g_{mb1} \tag{22}$$

The expressions for load resistors R1 and R2 show the factor of transconductance (G_{m1}) and output resistance R_{tail}. This just confirms the imbalance relationship of the differential active balun given the non-ideal current source M3. Output voltages v_{out1} and v_{out2} depend on the corresponding transconductances of M1 and M2. High transconductance would help mitigate the imbalance, but in turn would also increase the current consumption. Instead, a better way to address this problem is to set the efficiency in terms of gmoverId high enough. Increasing load resistors R1 and R2 would increase the voltage gains A_{v1} and A_{v2}, respectively. However, with the power consumption requirement, there will be a limit in the effectiveness of increasing R1 and R2.

Resistance R_{tail} of M3 is essentially the output impedance of M3 due to channel-length modulation. The expression is shown as

$$R_{tail} = \frac{1}{\lambda I_{DS3}} \tag{23}$$

To maximize R_{tail}, current flowing in M3 should be kept at minimum. Even so, high tail current is necessary to supply branch currents ensuring the transistor operations of M1 and M2. With transistor dimensions set identical for the branch transistors M1 and M2, final adjustments could be made at the output loads R1 and R2. Design tradeoffs are inevitable and are carefully considered in the design of the active balun.

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