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Harmonic Distortion Analysis of Common-Source/Drain Active Balun Circuit

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I. ACTIVE BALUN DESIGN OVERVIEW

A balun (balanced-unbalanced) circuit converts signals that are single-ended or unbalanced with respect to ground into signals that are differential or balanced with respect to ground, and/or vice versa. An ideal balun generates a pair of differential output signals of balanced amplitudes (0 dB gain difference) and phases (180° phase difference) from a single-ended input signal source. 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 [1-2]. One of the active balun topologies is the common-source/drain active balun circuit shown in Fig. 1.

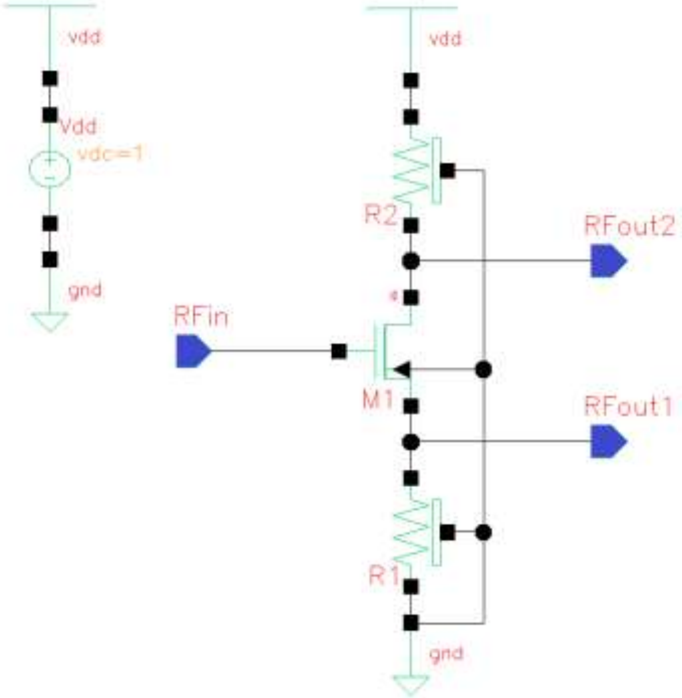

Fig. 1. Common-source/drain active balun circuit schematic.

The common-source/drain active balun is composed of just single transistor (M1) and is considered as the simplest topology amongst other active balun configurations. 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 shift 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.

II. TOTAL HARMONIC DISTORTION

An important parameter that should also be considered in the design of active balun is the total harmonic distortion (THD), which is a linearity parameter. It is the percentage of the inherent harmonics with respect to the fundamental signal. Ideally, THD is zero, but since this is not the case for transistors and transistor amplifiers, THD should then be minimized.

Let the total input voltage V_{in} be the sum of direct current (DC) input voltage (V_{IN}) and alternating current (AC) input voltage (v_{in}), as a function of time. AC input v_{in} could be further expressed as vrfcosωt, where vrf is the voltage peak value of v_{in}.

$$Vin(t) = V_{DC} + V_{AC} = V_{IN} + v_{in} = V_{IN} + vrf\cos\omega t \tag{1}$$

With simplified square-law equation, total drain current or drain-to-source current (I_{ds}) of the single transistor (M1) could be expressed as

$$I_{ds}(t) = \frac{\mu C_{ox}}{2}\frac{W}{L}[V_{in}(t) - V_t]^2 = \frac{\mu C_{ox}}{2}\frac{W}{L}[(V_{IN} + vrf\cos\omega t) - V_t]^2 \tag{2}$$

$$I_{ds}(t) = \frac{\beta}{2}(V_{IN} + vrf\cos\omega t - V_t)^2 \quad with\ \beta = \mu C_{ox}\frac{W}{L} \tag{3}$$

Expanding the expression of the drain current, substituting the 2nd order expression cos2ωt with its half-angle trigonometric equivalent, then rearranging according to n order, results to

$$I_{ds}(t) = \frac{\beta}{2}\left[\left((V_{IN} - V_t)^2 + \frac{vrf^2}{2}\right) + 2vrf(V_{IN} - V_t)\cos\omega t + \frac{vrf^2}{2}\cos 2\omega t\right] \tag{4}$$

It can be noted that the drain current has only three terms, if the signal stays within the square-law region.

$$I_{ds}(t) = I_0 + I_1\cos\omega t + I_2\cos 2\omega t \tag{5}$$

$$I_0 = \frac{\beta}{2}\left[(V_{IN} - V_t)^2 + \frac{vrf^2}{2}\right] = I_{DC} \quad \rightarrow \quad \text{DC term} \tag{6}$$

$$I_1 = \frac{\beta}{2}[2vrf(V_{IN} - V_t)] \quad \rightarrow \quad \text{Amplitude of 1st harmonic} \tag{7}$$

$$I_2 = \frac{\beta}{2}\left(\frac{vrf^2}{2}\right) \quad \rightarrow \quad \text{Amplitude of 2nd harmonic} \tag{8}$$

Since the derivation is only for a single transistor configuration, component V_{IN} is just equal to V_{GS} with the source node grounded. Hence, V_{IN} –V_t is also the overdrive voltage (V_{OV}). Transconductance (g_m) can also be derived from (7) where the expression is a linear function of vrf.

$$\frac{I_1}{vrf} = \frac{\beta}{2}[2(V_{IN} - V_t)] = \mu C_{ox}\frac{W}{L}(V_{IN} - V_t) = g_m \tag{9}$$

Succeeding expressions show computation for the THD of a single metal-oxide semiconductor field-effect transistor (MOSFET) amplifier, which for this case is up to 2nd harmonic component only.

$$THD = \sqrt{\frac{f_2^2}{f_1^2} + \frac{f_3^2}{f_1^2} + \cdots + \frac{f_n^2}{f_1^2}} = \frac{I_2}{I_1} = HD_2 = \frac{\frac{\beta}{2}\left(\frac{vrf^2}{2}\right)}{\frac{\beta}{2}[2vrf(V_{IN} - V_t)]} \tag{10}$$

$$THD = \frac{vrf}{4(V_{IN} - V_t)} = \frac{vrf}{4V_{OV}} \tag{11}$$

Expressing THD in terms of the efficiency (gmoverId),

$$THD = \frac{vrf}{4(V_{IN} - V_t)} = \frac{vrf}{4V_{OV}} = \frac{vrf}{8}\frac{g_m}{I_{DS}} \tag{12}$$

It can be observed that minimizing the overdrive voltage V_{OV} would result to higher THD. Increasing the efficiency in terms of gmoverId would also result to higher THD. With this, there is a limit in the effectiveness of optimizing V_{OV} and gmoverId to minimize the distortion.

In common-source/drain active balun, the source resistance (R1) provides local feedback. From (1) and (2), total drain current is expressed as

$$I_{ds}(t) = \frac{\beta}{2}[V_{GS} - V_t]^2 = \frac{\beta}{2}\{[(V_{IN} + v_{in}) - (V1 + v_{out1})] - V_t\}^2 \tag{13}$$

$$I_{ds}(t) = \frac{\beta}{2}\left\{\left[V_y{}^2 + \frac{vrf^2/2}{(1 + g_m R1)^2}\right] + \left(\frac{2vrf \cdot V_y}{1 + g_m R1}\right)\cos\omega t + \left(\frac{vrf^2/2}{(1 + g_m R1)^2}\right)\cos 2\omega t\right\} \tag{14}$$

$$with\ V_y = V_{IN} - V1 - V_t \tag{15}$$

The drain current has three terms, given as

$$I_{0f} = \frac{\beta}{2}\left[V_y{}^2 + \frac{vrf^2/2}{(1 + g_m R1)^2}\right] = I_{DC} \quad \rightarrow \quad \text{DC term} \tag{16}$$

$$I_{1f} = \frac{\beta}{2}\left[\frac{2vrf \cdot V_y}{1 + g_m R1}\right] \quad \rightarrow \quad \text{Amplitude of 1st harmonic} \tag{17}$$

$$I_{2f} = \frac{\beta}{2}\left[\frac{vrf^2/2}{(1 + g_m R1)^2}\right] \quad \rightarrow \quad \text{Amplitude of 2nd harmonic} \tag{18}$$

All three equations have a factor of 1/(1 + g_mR1) on its AC term vrf. The source resistance (R1) provides local feedback and the term g_mR1 is the loop gain (expressed as T). Equating expressions in (16) to (18) with their counterparts in (6) to (8),

$$I_{0f} = \frac{\beta}{2}\left[{V_y}^2 + \frac{vrf^2/2}{(1+T)^2}\right] \quad \rightarrow \quad \text{DC term} \tag{19}$$

$$I_{1f} = \frac{\beta}{2}\left(\frac{2vrf \cdot V_y}{1+T}\right) = \frac{I_1}{1+T} \quad \rightarrow \quad \text{Amplitude of 1st harmonic} \tag{20}$$

$$I_{2f} = \frac{\beta}{2}\left[\frac{vrf^2/2}{(1+T)^2}\right] = \frac{I_2}{(1+T)^2} \quad \rightarrow \quad \text{Amplitude of 2nd harmonic} \tag{21}$$

THD of the current-source/drain active balun could now be determined, which resembles that of a single amplifier with resistor feedback.

$$THD = \sqrt{\frac{f_2^2}{f_1^2} + \frac{f_3^2}{f_1^2} + \cdots + \frac{f_n^2}{f_1^2}} = \frac{I_{2f}}{I_{1f}} = HD_2 = \frac{\frac{\beta}{2}\left[\frac{vrf^2/2}{(1+T)^2}\right]}{\frac{\beta}{2}\left(\frac{2vrf \cdot V_y}{1+T}\right)} \tag{22}$$

$$THD = \frac{vrf}{4V_y(1+T)} = \frac{vrf}{4(V_{IN} - V1 - V_t)(1 + g_m R1)} \tag{23}$$

$$THD = \frac{vrf}{4V_{OV}(1 + g_m R1)} \tag{24}$$

Expressing THD in terms of gmoverId,

$$THD = \frac{vrf}{8(1 + g_m R1)} \frac{g_m}{I_{DS}} \tag{25}$$

The presence of source resistance (R1) would reduce the distortion, but would also reduce the gain (A_{v2}) of the common-source part of the active balun. However, increasing R1 would also minimize the attenuation (A_{v1}) of the common-drain part of the active balun. Moreover, from (24), minimizing the overdrive voltage (V_{OV}) tends to increase the distortion. In addition, increasing the efficiency in terms of gmoverId would also result to higher THD. Ultimately, there is a limit in the effectiveness of optimizing R1, V_{OV}, and gmoverId to minimize the distortion.

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