Load-Modulated Balanced Power Amplifiers - Files and Basic Mathematics

by

Ryan Swanson

Boulder, Colorado

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Chapter 1

Introduction

With 5G and 6G systems on the horizon, it is vital to build cohesive wide-band systems that can operate in the near future. This work is meant to analyze the bandwidth limitations of a new topology of Power Amplifier, the Load Modulated Balanced Amplifier. Assuming that the transistors in use operate over a wide bandwidth, the remaining components will constrict device performance. Thus this work will analyze the negative impact of nonidealities found within the LMBA, specifically coupler balance which will be discussed later.

1.1 Included With This Document

There are three major components found within this email. The first of which is this document.

Here you will find a detailed analysis of the building blocks fundamental to LMBA design. Hopefully, you will be able to pick up the fundamentals easier with the mathematical steps provided here. After the theoretical section is where the remaining objectives are found.

The second component to this email are the books and papers. RF Power Amplifiers for Wireless Communications by Steve Cripps is a great place to start. Several LMBA papers are included as well as Microwave Engineering by David Pozar. Pozar's book is a great place to find a detailed analysis of Balanced Amplifiers.

Finally, the simulation work-spaces are provided. This is broken into three parts. The first is the LMBA_FinalProject. This workspace utilizes ADS to build up a basic LMBA with a Class AB amplifier as its base. This is where you would want to start as it is a the simplest LMBA design.

The second workspace is the LMBA_ThesisWork. This includes additional matching that is utilized to implement wide-band transistor techniques. This is the heart of this work. The final workspace is LMBA_Ideal. This was used to analyze the ideal conditions of the LMBA which was compared to mathematical analysis. Here you will find a breakdown from current sources and ideal couplers, to a S-Parameter block that captures nonideal coupler imbalance.

Chapter 2

Theory of Operation

This paper uses two techniques that are discussed here to measure the bandwidth of the device. The first of which are the basic principles of the LMBA while the second is an Amplifier Design technique that allows for operation of a wide-bandwidth transistor.

2.1 Quadrature Hybrid Coupler

The Quadrature Hybrid Coupler is the foundation of the LMBA. It allows for the "Balanced Amplifier" concept and is the heart of the LMBA. The Coupler can be used as a 3dB power splitter with a 90 degree phase shift between the output currents. The basic topology of the coupler is seen below in Figure 2.1. The operation of this device can be determined using Even-Odd mode analysis but is not repeated here.

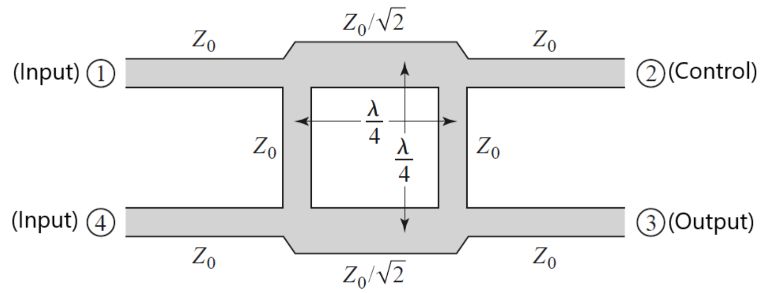

Figure 2.1: Topology of Quadrature Hybrid Coupler

The resulting scattering matrix of the device is seen below.

$$[S] = \frac{-1}{\sqrt{2}} \begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix}$$

It is, however, easier to think about this device in a Z-Matrix configuration. This will help with later analysis. Thus, let us find the appropriate Z-Matrix of the device. The conversion between the [S] and [Z] matrix is as follows:

$$Z = ([S] + [U])([U] - [S])^{-1}$$

where [U] is the unity matrix. Performing the Math reveals the following Matrix:

$$[Z] = \begin{bmatrix} 1 & \frac{-j}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & 0 \\ \frac{-j}{\sqrt{2}} & 1 & 0 & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{2}} & 0 & 1 & \frac{-j}{\sqrt{2}} \\ 0 & \frac{-1}{\sqrt{2}} & \frac{-j}{\sqrt{2}} & 1 \end{bmatrix} * \begin{bmatrix} -1 & \frac{-j}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & 0 \\ \frac{-j}{\sqrt{2}} & -1 & 0 & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{2}} & 0 & -1 & \frac{-j}{\sqrt{2}} \\ 0 & \frac{-1}{\sqrt{2}} & \frac{-j}{\sqrt{2}} & -1 \end{bmatrix}^{-1}$$

Reducing further:

$$[Z] = \begin{bmatrix} 1 & \frac{-j}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & 0 \\ \frac{-j}{\sqrt{2}} & 1 & 0 & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{2}} & 0 & 1 & \frac{-j}{\sqrt{2}} \\ 0 & \frac{-1}{\sqrt{2}} & \frac{-j}{\sqrt{2}} & 1 \end{bmatrix} * \begin{bmatrix} \frac{1}{2} & \frac{-j}{\sqrt{2}} & 0 & \frac{j}{2} \\ \frac{-j}{\sqrt{2}} & \frac{1}{2} & \frac{j}{2} & 0 \\ 0 & \frac{j}{2} & \frac{1}{2} & \frac{-j}{\sqrt{2}} \\ \frac{j}{2} & 0 & \frac{-j}{\sqrt{2}} & \frac{1}{2} \end{bmatrix}$$

Performing this multiplication reveals the resulting impedance matrix to be equal to:

$$[Z] = Z_0 \begin{bmatrix} 0 & -j\sqrt{2} & 0 & j \\ -j\sqrt{2} & 0 & j & 0 \\ 0 & j & 0 & -j\sqrt{2} \\ j & 0 & -j\sqrt{2} & 0 \end{bmatrix}$$

2.2 Balanced Amplifier

The Balanced Amplifier configuration is versatile because of the "disapearing" reflection coefficient. As described in Pozar, and assuming similar reflection coefficients at the transistor planes, the phase shifting of the coupler provides destructive interference at the input and output ports. The Balanced amplifier, while important to this work, is not repeated here.

2.3 Load Modulated Balanced Amplifier

The Load Modulated Balanced Amplifier is the heart and soul of this work. It replaces the load resistor on the output coupler, in a balanced amplifier configuration, with a current source, also called the Control Signal Power (CSP). The topology can be seen in Figure 2.2 below.

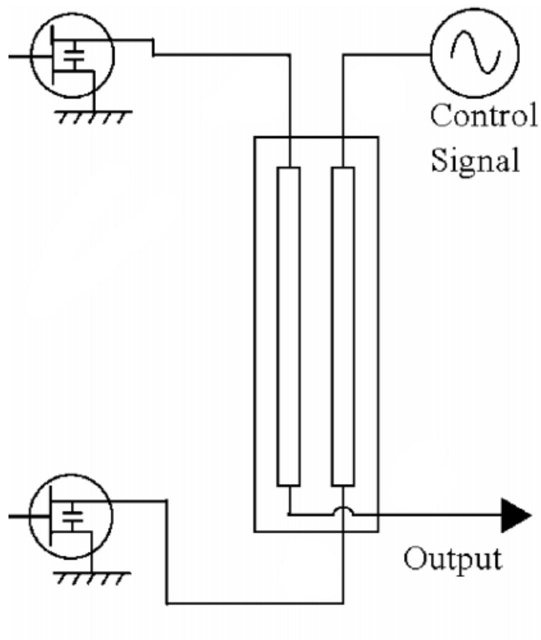

Figure 2.2: Coupler Performance [Cripps]

2.3.1 BA Load Modulation

Here we will define the load modulation that is performed by the device. As discussed in section 2.1, the impedance matrix of the device has the form seen below. Here it is worth noting that the current into Ports 1 and 4 of the device are equal to jIb and -Ib respectively (due to phase shift from unseen input coupler). The current into port 2 is equal to Ic, the CSP output current. Finally the current into port 3 is equal to the negative of the output current! Note that the current at the output is equal to (j(2$\frac{1}{\sqrt{2}}$Ib + Ic)). Subtraction and imaginary component is due to phase shifting of the coupler. Now lets solve for the input impedances presented to the devices.

$$\begin{bmatrix} V1 \\ V2 \\ V3 \\ V4 \end{bmatrix} = Z_0 \begin{bmatrix} 0 & -j\sqrt{2} & 0 & j \\ -j\sqrt{2} & 0 & j & 0 \\ 0 & j & 0 & -j\sqrt{2} \\ j & 0 & -j\sqrt{2} & 0 \end{bmatrix} * \begin{bmatrix} -jIb \\ Ic \\ -Iout \\ -Ib \end{bmatrix}$$

Currently, we only care about the impedance seen at ports 1 and 4, thus we will only perform those multiplications. We find the following two equations for those outputs:

$$V_1 = Z_0(-jIb - j\sqrt{2}Ic)$$

$$V_4 = Z_0(j\sqrt{2}Iout + Ib) = Z_0(-\sqrt{2}(\frac{2}{\sqrt{2}}Ib + Ic) + Ib) = Z_0(-\sqrt{2}Ic - Ib)$$

Reducing these equations into impedances reaveals:

$$\frac{V_1}{I_1} = \frac{V_1}{-jIb} = Z_1 = Z_0(1 + \sqrt{2}\frac{Ic}{Ib})$$

$$\frac{V_4}{I_4} = \frac{V_4}{-Ib} = Z_4 = Z_0(1 + \sqrt{2}\frac{Ic}{Ib})$$

From the above, we easily see that the input impedance at ports 1 and 4 are identical. An incredible result which means that we can modulate the impedances seen by the balanced amplifiers equally. It is worth noting, however, that these components assume perfect current sources. Amplifiers have a different impedance than a current source and thus the impedance circles will have different shapes dependent upon the load presented to the ports.

2.3.1.1 CSP Load Impedance

Now lets briefly find the load impedance presented to the CSP. In its current configuration, we need to find the voltage V_2:

$$V_2 = -jZ_0\sqrt{2} * (-jIb) - jZ_0 I_{out} = -\sqrt{2}Z_0 I_b - jZ_0 * j(\sqrt{2}I_b + I_c)$$

Note, the I_b currents cancel and we are left with:

$$V_2 = Z_0 I_c$$

Now we can easily find the impedance presented to each port by diving both sides by I_c:

$$\frac{V_2}{I_c} = Z_{CSP} = Z_0$$

2.3.1.2 Device Output Power

Note, the real power found at the at each of the balanced ports is calculated as (assuming I_b is purely real):

$$P_{bal} = I_b^2 * Re\{Z_{bal}\}$$

$$P_{bal} = I_b^2 * Re\left\{Z_0\left(1 + \sqrt{2}\frac{Ic}{Ib}\right)\right\}$$

Thus, the resulting power at the balanced ports is equal to:

$$2P_{bal} = Z_0(I_b^2 + \sqrt{2}I_b * Re\{I_c\}) = Z_0(I_b^2 + \sqrt{2}I_b I_c \cos(\theta))$$

Now we can find the power found at the load of the LMBA. Assuming that the load is matched to the impedance of the coupler, Z_0, and the current at the output is equal to $\sqrt{2}I_b$ + I_c:

$$P_{Load} = \frac{1}{2}Z_0|I_{out}|^2 = \frac{1}{2}Z_0|\sqrt{2}I_b + I_c|^2 = \frac{1}{2}Z_0|\sqrt{2}I_b + I_c\cos\theta + jI_c\sin\theta|^2$$

Expanding the above reveals:

$$P_{Load} = Z_0\left(I_b^2 + \sqrt{2}I_bI_c\cos\theta + \frac{1}{2}I_c^2\right)$$

Since the power at the control port is equal to $\frac{1}{2}I_c^2Z_0$, we can see that the power at the load is P_{Load} = 2P_{bal} + P_{con}. A remarkable result, as all of the power is found at the output of the device!

2.3.2 Non-Ideal Case, Perfectly Matched, Load Modulation

Now lets assume that the device has non-ideal isolation between the balanced amplifier ports. We will assume that isolation is imperfect between ports 1 and 4 of Figure 2.1 (i.e. the transport between these ports is a small value δ). The S-Matrix of this coupler is seen as:

$$[S] = \frac{-1}{\sqrt{2}}\begin{bmatrix} 0 & j & 1 & j\delta \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ j\delta & 1 & j & 0 \end{bmatrix}$$

Using the same methodology as in section 2.1, we find a complicated matrix with δ terms of high orders. Since δ is small, we can approximate the high order values as zero! Thus, we find the resulting impedance matrix to be equal to:

$$[Z] = [TBD]$$

Now we can find a generalized expression for a system with non-ideal isolation between ports 1 and 4 and between ports 2 and 3. Here we assume that the transmission is a small value δ between ports 1 and 4 and a small value α between ports 2 and 3. The resulting S-Matrix is seen as:

$$[S] = \frac{-1}{\sqrt{2}} \begin{bmatrix} 0 & j & 1 & j\delta \\ j & 0 & j\alpha & 1 \\ 1 & j\alpha & 0 & j \\ j\delta & 1 & j & 0 \end{bmatrix}$$

Using the same methodology as above (assuming high-order δ, α, and $\delta * \alpha$ terms are zero), along with mathematical software to perform large calculations, we find the resulting impedance matrix:

$$[Z] = Z_0 \begin{bmatrix} \frac{1}{\sqrt{2}}\delta & -j(\frac{1}{2}(\alpha+\delta)+\sqrt{2}) & -\frac{1}{2}(\alpha+\delta) & j(\frac{1}{\sqrt{2}}\alpha+1) \\ -j(\frac{1}{2}(\alpha+\delta)+\sqrt{2}) & \frac{1}{\sqrt{2}}\alpha & j(\frac{1}{\sqrt{2}}\delta+1) & -\frac{1}{2}(\alpha+\delta) \\ -\frac{1}{2}(\alpha+\delta) & j(\frac{1}{\sqrt{2}}\delta+1) & \frac{1}{\sqrt{2}}\alpha & -j(\frac{1}{2}(\alpha+\delta)+\sqrt{2}) \\ j(\frac{1}{\sqrt{2}}\alpha+1) & -\frac{1}{2}(\alpha+\delta) & -j(\frac{1}{2}(\alpha+\delta)+\sqrt{2}) & \frac{1}{\sqrt{2}}\delta \end{bmatrix}$$

Now that we have found the resulting impedance matrix for the non-ideal coupler, we can find the load modulation performed by the non-ideal device.

$$\begin{bmatrix} V1 \\ V2 \\ V3 \\ V4 \end{bmatrix} = Z_0 \begin{bmatrix} \frac{1}{\sqrt{2}}\delta & -j(\frac{1}{2}(\alpha+\delta)+\sqrt{2}) & -\frac{1}{2}(\alpha+\delta) & j(\frac{1}{\sqrt{2}}\alpha+1) \\ -j(\frac{1}{2}(\alpha+\delta)+\sqrt{2}) & \frac{1}{\sqrt{2}}\alpha & j(\frac{1}{\sqrt{2}}\delta+1) & -\frac{1}{2}(\alpha+\delta) \\ -\frac{1}{2}(\alpha+\delta) & j(\frac{1}{\sqrt{2}}\delta+1) & \frac{1}{\sqrt{2}}\alpha & -j(\frac{1}{2}(\alpha+\delta)+\sqrt{2}) \\ j(\frac{1}{\sqrt{2}}\alpha+1) & -\frac{1}{2}(\alpha+\delta) & -j(\frac{1}{2}(\alpha+\delta)+\sqrt{2}) & \frac{1}{\sqrt{2}}\delta \end{bmatrix} \begin{bmatrix} -jIb \\ Ic \\ -Iout \\ -Ib \end{bmatrix}$$

We will start by looking at the balanced amplifier ports (ports 1 and 4). This result becomes:

$$\frac{V_1}{Z_0} = \frac{\delta}{\sqrt{2}}(-jI_b) - j(\frac{1}{2}(\alpha+\delta)+\sqrt{2})I_c - \frac{1}{2}(\alpha+\delta)(-I_{out}) + j(\frac{1}{\sqrt{2}}\alpha+1)(-I_b)$$

$$\frac{V_4}{Z_0} = j(\frac{1}{\sqrt{2}}\alpha+1)(-jI_b) - \frac{1}{2}(\alpha+\delta)I_c - j(\frac{1}{2}(\alpha+\delta)+\sqrt{2})(-I_{out}) + \frac{1}{\sqrt{2}}\delta(-I_b)$$

Reducing reveals:

$$\frac{V_1}{Z_0} = -j\left(\frac{\delta+\alpha}{\sqrt{2}}+1\right)I_b - j\left(\frac{1}{2}\left(\alpha+\delta\right)+\sqrt{2}\right)I_c + \frac{1}{2}(\alpha+\delta)I_{out}$$

$$\frac{V_4}{Z_0} = \left(\frac{\alpha-\delta}{\sqrt{2}}+1\right)I_b - \frac{1}{2}(\alpha+\delta)I_c + j\left(\frac{1}{2}(\alpha+\delta)+\sqrt{2}\right)I_{out}$$

Note again that I_{out} is equal to $j(\sqrt{2}I_b + I_c)$ and by plugging in, we get the following result:

$$\frac{V_1}{Z_0} = -j\left(\frac{\delta+\alpha}{\sqrt{2}}+1\right)I_b - j\left(\frac{1}{2}\left(\alpha+\delta\right)+\sqrt{2}\right)I_c + \frac{j}{2}(\alpha+\delta)(\sqrt{2}I_b+I_c)$$

$$\frac{V_4}{Z_0} = \left(\frac{\alpha-\delta}{\sqrt{2}}+1\right)I_b - \frac{1}{2}(\alpha+\delta)I_c - \left(\frac{1}{2}(\alpha+\delta)+\sqrt{2}\right)(\sqrt{2}I_b+I_c)$$

Thus reduces further to:

$$\frac{V_1}{Z_0} = -jI_b - j\sqrt{2}I_c$$

$$\frac{V_4}{Z_0} = -(\delta\sqrt{2}+1)I_b - (\alpha+\delta+\sqrt{2})I_c$$

Thus, the impedance equations become:

$$Z_1 = Z_0\left(1+\sqrt{2}\frac{I_c}{I_b}\right)$$

$$Z_4 = Z_0\left((1+\delta\sqrt{2}) + (\sqrt{2}+\alpha+\delta)\frac{I_c}{I_b}\right)$$

As a final note, this is not quite the response seen within the AWR workspace. This needs to be resolved before completion.

Chapter 3

Remaining Objectives

As a last note, the remaining objectives will be stated here. For this work to be completed, the following must occur:

1. Resolve final Mathematical Errors at the End of Section 2 above
2. Calculate Phase and Amplitude required for LMBA response in LMBA_ThesisWork.
3. Fabricate Both LMBA Workspaces and Coupler Topologies
4. Run Tests on Both LMBAs with Different Couplers
5. Write and Present