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Byron Montgomery
Iowa State University

Yifei Li
Iowa State University

Nathan M. Neihart
Iowa State University, neihart@iastate.edu

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Abstract

Concurrent dual-band switch-mode power amplifiers require high common-mode impedance at their intermodulation frequencies. Baluns utilizing quarter-wave effects only have perfect open common-mode impedance at their design frequency. Attempting to use a balun without taking the new dual-band requirements for common-mode impedance into account will result in efficiency loss. However, the addition of some transmission lines can add impedance at those specific frequencies by rotation of the common-mode impedance without affecting the differential mode match.

Keywords

Baluns, Class-D, Dual-band, Power Amplifiers, Push-pull

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Common-Mode Termination Requirements in Concurrent Dual-Band Push-Pull Power Amplifiers

Byron Montgomery, Yifei Li, and Nathan M. Neihart
Dept. of Electrical and Computer Engineering
Iowa State University
Ames, IA, USA
{byronm, yifei, neihart}@iastate.edu

***Abstract*—Concurrent dual-band switch-mode power amplifiers require high common-mode impedance at their intermodulation frequencies. Baluns utilizing quarter-wave effects only have perfect open common-mode impedance at their design frequency. Attempting to use a balun without taking the new dual-band requirements for common-mode impedance into account will result in efficiency loss. However, the addition of some transmission lines can add impedance at those specific frequencies by rotation of the common-mode impedance without affecting the differential mode match.**

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I. Introduction

In response to ever increasing demands for higher bandwidth on cellular devices, the 3rd Generation Partnership Project has released definitions for carrier aggregation bands in LTE-advanced. These new definitions allow mobile phones to transmit on multiple bands simultaneously, increasing bandwidth and thus bitrate. In order to support these carrier aggregation standards, current front-end manufacturers have designed several separate RF paths, each with their own amplifiers and switches, transmitting and receiving simultaneously. Having multiple power amplifiers (PAs) not only significantly increases the required area, it also increases the complexity by introducing multiple paths that all require isolation from one another. Recently, however, designers have proposed solutions that use a single amplifier to transmit on multiple frequencies in an effort to save space and reduce complexity [1, 2].

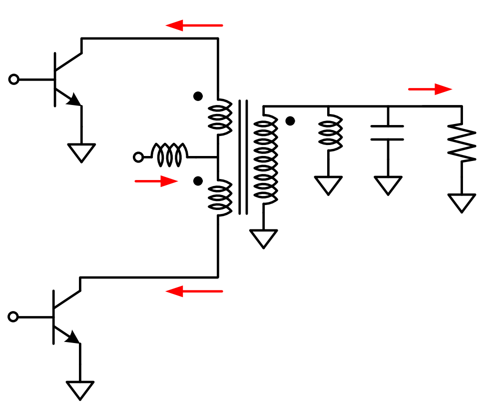

Figure 1: Schematic of a generic push-pull power amplifier using a transformer as a differential to single-ended converter.

In applications requiring high output power and high efficiency, a push-pull class-D amplifier could be used. Push-pull architectures have the key benefit of an added 3 dB of output power while simultaneously reducing noise from even harmonics [3]. Because the antenna is often single-ended, push-pull PAs generally require a transformer or balun for differential to single-ended conversion. However, high quality transformers are difficult to realize at RF frequencies. For example, ferrite cores are limited to frequencies less than 500 MHz and without a ferro-magnetic core, higher frequency transformers become lossy and bulky. As an alternative, designers have turned to capacitively coupled planar baluns.

For a push-pull amplifier, however, the common mode signal needs to be presented with a high impedance, otherwise power will leak through the common-mode terminal and overall efficiency will be degraded [4]. High common-mode impedance is something nearly all baluns accomplish at harmonic frequencies, but dual-band PAs have additional requirements, namely their common-mode signals contain 2nd- and 4th-order intermodulation (IM) components as well. Management of IM components in balun design has been studied, but never in the context of concurrent dual-band PA design [5]. Moreover, while there are many dual-band balun designs that seemingly satisfy all of the necessary requirements [6, 7], these baluns still result in poor efficiency when used in concurrent dual-band PAs and this degradation has never been fully explained.

This paper analyzes the effect of common-mode termination impedances in a push-pull class-D PA in terms of the relative magnitude of the termination impedance for different non-linear components. As the common-mode impedance changes, the power leakage through the common-mode terminal of the balun changes and this change is expressed as a drop in collector efficiency. Finally, this paper presents a method for modifying traditional Marchand baluns to improve their common-mode termination qualities when used in concurrent dual-band push-pull power amplifiers.

II. Termination Requirements In Push-Pull Amplifiers.

In order to understand why dual-band power amplifiers need special consideration, this section will first review the operation of a single-band class-D push-pull power amplifier and then compare them with concurrent dual-band class-D push-pull power amplifiers.

A. Single-Band Push-Pull Class-D Power Amplifiers

Consider the simplified current-switched, push-pull Class-D PA is shown in Fig. 1. It is assumed that the transistors behave as ideal switches with instantaneous switching, zero saturation voltage, zero ON resistance, and infinite OFF resistance. In addition, it is assumed that the RF-choke (RFC) inductor has infinite inductance and forces a relatively constant current, I_{DC}.

In the single-band case, the differential input can be expressed as:

$$V_{in}^{+} = sgn[\sin(\omega_0 t)] \quad (1)$$

$$V_{in}^{-} = -sgn[\sin(\omega_0 t)]. \quad (2)$$

In this case, the collector currents, I_C^+ and I_C^-, are simply phase shifted square waves alternating between zero and I_{DC}, as seen in Fig. 2. For convenience it is assumed that the transformer, TX_1, is ideal with turns ratio of 1:1 and that the LC tank comprised of L and C resonates at ω_0 with infinite Q. Under these conditions, the load current is purely sinusoidal and can be expressed as:

$$I_L = \frac{4}{\pi} I_{DC} \sin(\omega_0 t) \quad (3)$$

which will induce a load voltage of:

$$V_L = I_L R = \frac{4}{\pi} I_{DC} R \sin(\omega_0 t). \quad (4)$$

Notice in Fig. 1, that V_L is also dropped across the secondary winding of the transformer and will therefore be reflected back to the primary, resulting in a primary voltage waveform that has both a differential and common-mode component. The differential voltage is dropped across the transistors and is given by:

$$V_{ce}^{+} = \begin{cases} 2V_L \sin(\omega_0 t) & for\ 0 \le t \le T/2 \\ 0 & for\ T/2 < t < T \end{cases} \quad (5)$$

$$V_{ce}^{-} = \begin{cases} 0 & for\ 0 < t < T/2 \\ -2V_L \sin(\omega_0 t) & for\ T/2 \le t \le T \end{cases} \quad (6)$$

where T is the period of the carrier frequency. These waveforms are also plotted in Fig. 2.

Finally, the common-mode voltage appears at the center-tap of the transformer and is a full-wave rectified version of the output:

$$V_C = \frac{V_{ce}^{+} + V_{ce}^{-}}{2} = |V_L \sin(\omega_0 t)|. \quad (7)$$

It is this common-mode voltage that will prove to be the primary difference between the load design of a single-band and concurrent dual-band push-pull PA. The Fourier series of V_C in (7):

$$|V_L \sin(\omega_0 t)| = \frac{2V_L}{\pi} - \frac{4V_L}{\pi} \sum_{n=2,4,\ldots}^{\infty} \frac{\cos(n\omega_0 t)}{n^2 - 1}. \quad (8)$$

It is seen from (8) that the common-mode voltage consists of a DC term and even-order harmonics. These even-order harmonics must be terminated in a high-impedance, otherwise

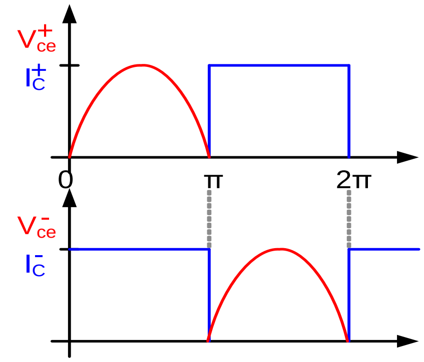

Figure 2: Collector current and collector voltage for ideal single-band push-pull class-D power amplifier.

power will leak through the common-mode output and reduce efficiency.

B. Dual-Band Push-Pull Class-D Power Amplifiers

We now turn our attention to examining the common-mode termination requirements for a concurrent dual-band push-pull Class-D PA. The schematic shown in Fig. 1 is also used in this analysis, however, the input signal is now given as the sum of two sinusoids, each with different frequency:

$$V_{in}^{+} = sgn[\sin(\omega_1 t) + \sin(\omega_2 t)] \quad (9)$$

$$V_{in}^{-} = -sgn[\sin(\omega_1 t) + \sin(\omega_2 t)] \quad (10)$$

where ω_1 and ω_2 are the two operation frequencies of interest.

Using the same approach as before, we can express the load voltage as:

$$V_L = I_{fun1} R \sin(\omega_1 t) + I_{fun2} R \sin(\omega_2 t) \quad (11)$$

where I_{fun1} and I_{fun2} are the amplitudes for the differential collector current obtained from the Fourier series, and are assumed to be equal. It is interesting to note, that under ideal concurrent dual-band operation, the differential output current can take on three distinct levels:

$$I_{DIF} = \begin{cases} I_{DC}/2 & V_{in}^{+} > 0 \text{ and } V_{in}^{-} < 0 \\ -I_{DC}/2 & V_{in}^{+} < 0 \text{ and } V_{in}^{-} > 0. \\ 0 & V_{in}^{+} = V_{in}^{-} = 0 \end{cases} \quad (12)$$

Because of this, finding the Fourier series of I_{DIF} is complicated and due to space constraints is omitted here. From (11), we can express the common-mode voltage at the center tap of the transformer, as:

$$V_C = \left| i_{fund1} R \sin(\omega_1 t) + i_{fund2} R \sin(\omega_2 t) \right|. \quad (13)$$

Examining the Fourier series of (13), shows that V_C consists of a DC component, two fundamentals (at ω_1 and ω_2), even harmonics of both fundamentals, and, most importantly, intermodulation (IM) components. The presence of the additional harmonics and the IM components dramatically complicates the common-mode termination requirements when compared to the single-band case. It is worth noting that the presence of the harmonic and IM components in V_C is not due to the nonlinear switches, but instead due to the intrinsic behavior of the balun/transformer and will therefore be present even in push-pull, linear (e.g., class-B) PAs.

TABLE I. REDUCTION IN EFFICIENCY DUE TO COMMON-MODE POWER LEAKAGE AS A FUNCTION OF COMMON-MODE TERMINATION IMPEDANCE

Common-mode Termination	Common-Mode Component (f_2>f_1)					
	f_1 +f_2	-2f_1 +2f_2	2f_1	-f_1 +f_2	2f_2	2f_1 +2f_2
R_L/10	-39%	-11%	-18%	-35%	-17%	-11%
R_L/5	-27%	-5.8%	-11%	-24%	-9%	-6%
R_L/2	-13%	-2%	-5%	-12%	-4%	-2%
R_L	-7%	-1%	-2%	-7%	-2%	-1%
2R_L	-4%	-1%	-2%	-3%	-1%	-1%
5R_L	-1%	<-1%	<-1%	-1%	<-1%	<-1%
10R_L	-1%	<-1%	<-1%	<-1%	<-1%	<-1%

Under ideal circumstances, when all of the common-mode voltage components are terminated in open-circuits, the collector efficiency is 100%. Two potential problems arise however: 1) it is impractical to terminate all possible harmonic and IM components of V_C; 2) it may be difficult to achieve an open-circuit termination. Common sense tells us that the efficiency is likely to be dominated by only a subset of these frequency components and that the termination impedance value must only be "high enough."

The collector efficiency for a concurrent dual-band amplifier can be expressed as:

$$\eta = \frac{P_{\omega 1}+P_{\omega 2}}{P_{DC}} \quad (14)$$

where $P_{\omega 1}$ is the RF output power at ω_1, $P_{\omega 2}$ is the RF output power at ω_2, and P_{DC} is the power supplied from the DC source. The effects of common-mode power leakage are examined through numerical analysis using Matlab. The process involves first computing the Fourier series coefficients of the common-mode voltage and then terminating each component, one at a time, with a variable impedance normalized to the load resistance, while all other frequency components are terminated in ideal open-circuits. At each step, the new RF output power at each fundamental is calculated and the resulting collector efficiency is obtained from (14). The resulting drop in efficiency is shown in Table I for the case where $f_1 = 1\,GHz$, $f_2 = 1.5$ GHz, and up to 4^{th}-order nonlinearities are considered.

It is seen that the 2^{nd} harmonic and IM2 terms have the largest impact on overall collector efficiency and should be terminated with an impedance of at least $10R_L$ in order to limit the efficiency degradation to less than 1%. The IM4 components, on the other hand, should be terminated with an impedance of at least $2R_L$. It was found that the effects of 6^{th}-order and higher nonlinearities had a negligible impact on efficiency degradation. In the previous analysis, it was assumed that the two carriers have equal magnitude. An imbalance in the magnitude of the two carriers will alter the relative importance of the various harmonic and IM components and the efficiency calculations would need to be repeated. Next, a method for controlling the common-mode impedance of a traditional planar balun is presented.

III. BALUN DESIGN FOR COMMON-MODE IMPEDANCE

Planar baluns utilize the properties of coupled transmission lines and quarter-wave effects to approximate the behavior of an ideal transformer. A well-designed balun has low insertion loss, near equal amplitude/phase balance, and high CMRR. A common balun structure is known as the Marchand balun and a simplified diagram is shown in Fig. 3 [6]. Marchand originally designed his balun using two $\lambda/4$ coaxial transmission lines. Since then, several papers have been published implementing planar Marchand baluns [8-10].

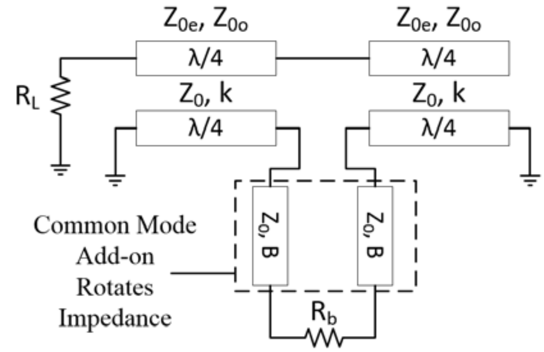

Figure 3: Block diagram of Marchand balun showing the proposed common-mode add-on.

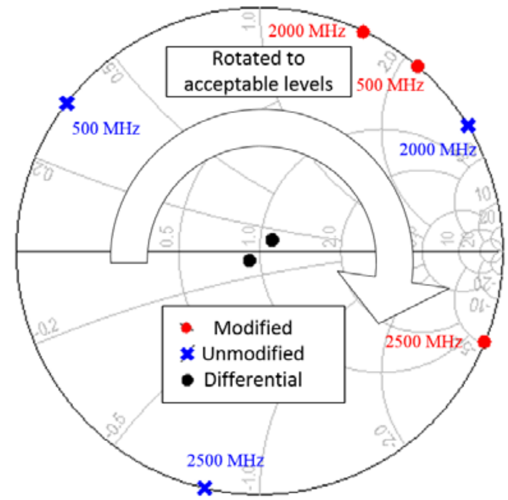

Figure 4: Smith chart showing the movement of common-mode and differential-mode impedance with the common-mode changes.

One notable drawback to the Marchand balun is the lack of an explicit common-mode terminal. Due to the geometry of the balun, the common-mode signal does not couple to the unbalanced port [9]. Instead, it is terminated by a short-circuited $\lambda/4$ piece of transmission line with impedance:

$$Z_{SC} = jZ_0 \tan\left(\frac{2\pi}{\lambda}\ell\right) \quad (10)$$

where ℓ is the physical length of the transmission line and λ is the wavelength of the frequency of interest. For the single-band case, the periodic nature of $\lambda/4$ transmission lines presents the correct common-mode termination at all frequencies. The concurrent dual-band case, however, is different. Because the harmonics and the IM components are not integer multiples of each other, the $\lambda/4$ transmission line will result in the common-mode impedance rotating around the outside edge of the Smith chart, leaving many common-mode components terminated in impedances near the short-

TABLE II. IDEAL CLASS-D EFFICIENCY WITH BALUN

Balun	Efficiency
Ideal	93.0%
Without Modifications	53.0%
With Modifications.	80.5%

circuit.

To illustrate the problem, an unmodified wideband Marchand balun is designed to operate at both 1 GHz and 1.5 GHz, simultaneously. The common mode impedance is simulated using Keysight's Advanced Design System (ADS) and plotted on a Smith chart in Fig. 4. Notice that the IM2 components at 500 MHz ($f_1 - f_2$) and 2500 MHz ($f_1 + f_2$) are relatively close to the short-circuit side of the Smith chart. Assuming a $50\,\Omega$ load, the approximate impedances at these two frequencies is $0.03 + j17\,\Omega$ and $0.002 - j39.6\,\Omega$ which, from Table I, will lead to a significant reduction in overall efficiency. It is interesting to point out that this balun still has a high CMRR (approximately 30 dB), illustrating that the CMRR is not a good predictor for correct common-mode termination for concurrent dual-band signals.

Fortunately, the common-mode impedance of the Marchand balun can be modified in order to make it suitable for use in concurrent dual-band push-pull amplifiers. In order to increase the common-mode impedance without significantly increasing the insertion loss of the balun, a pair of uncoupled transmission lines can be added to the balanced port, denoted the common-mode add-on in Fig. 3. The characteristic impedance of the common-mode add-on should be set to $Z_0 = R_b/2$ where R_b is the balanced load impedance. This will have the effect of rotating the common-mode impedance around the outer edge of the Smith chart towards the open-circuit while the differential-mode impedances stay fixed in the center.

To demonstrate the improvements of the common-mode add-on, two baluns were designed, using ADS Momentum on a Rogers RO3003 substrate, to operate at 1 GHz and 1.5 GHz, simultaneously. The first balun is an unmodified Marchand balun and has a common-mode impedance of $0.03 + j17\,\Omega$ at 500 MHz and $0.002 - j39.6\,\Omega$ at 2500 MHz. The second balun includes the common-mode add-on and the common-mode impedances at 500 MHz and 2500 MHz are increased $0.28 + j279\,\Omega$ at 500 MHz and $3.2 - j527\,\Omega$ at 2500 MHz, respectively.

These baluns were then included in an ideal concurrent dual-band, push-pull class-D power amplifier with a $50\,\Omega$ load, that was designed to operate at 1 GHz and 1.5 GHz, simultaneously. Three separate simulations were performed and the collector efficiency for each case is shown in Table II. The first simulation used ideal open-circuit terminations for all common-mode voltage components in the PA. The efficiency in this case was 93%. The efficiency is not 100% in this case due to slight inaccuracies in the simulation. The second simulation used the unmodified Marchand balun and the simulated collector efficiency is 53%. Finally, the PA was simulated using the Marchand balun with the common-mode add-on, and the collector efficiency increased to 81%, an increase of 28%. These values are well predicted by Table I.

IV. CONCLUSION

This paper quantified the effects of common-mode leakage on collector efficiency in concurrent dual-band push-pull class-D power amplifiers. It was seen that 2^{nd}-order nonlinearities produced by the load voltage reflecting across the balun must be terminated in at least $10R_L$ in order to limit the efficiency degradation to less than 1%. Likewise 4^{th}-order nonlinearities must be terminated, but they may be terminated in impedances as low as $2R_L$. Higher-order nonlinearities were found to be negligible in their impact on overall efficiency. This paper also presented an improved Marchand balun design technique that can be used to improve the common-mode termination behavior of such baluns when used in concurrent dual-band push-pull power amplifiers.

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