

# A 60-GHz Power Amplifier With Efficiency Enhancement at Power Back-off

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**Abstract**—This paper presents a 60-GHz CMOS power amplifier (PA) with efficiency enhancement at power back-off. To boost the amplifier performance at millimeter-wave (mm Wave) frequencies, the neutralized amplifier stage is optimized with input transformer. Furthermore, the power combining techniques are used to enlarge the output power and enhance the efficiency at power back-off as well. The transformer-based power-combining PA consists of several unit amplifiers, operating in Class AB for both good back-off efficiency and linearity.

**Index Terms**—60-GHz, power amplifier, CMOS, Class AB, efficiency, linearity, back-off, power combining, transformer

## I. INTRODUCTION

As an unlicensed band, 60-GHz has a promising prospect in the application of multi-Gbps wireless communications, invoking the standardizations (eg. IEEE802.15.3c, IEEE 802.11ad and ECMA-387) and industry-led consortia (eg. WiGig and WirelessHD). The development of silicon technology makes it possible to use CMOS technology for compact-size and low-cost design of 60-GHz power amplifier (PA) nowadays [1]-[2].

Despite numerous publications about 60-GHz power amplifier, there is still a great challenge to provide high output power for potential wireless application of long distance [3]. One of the most popular method to overcome this challenge is power combining. However, most of these power combining PA designs either cannot work in 60-GHz band, or their efficiency drops rapidly when output power is backed off from the single point [2]-[5]. A recent 0.75-2.0 GHz PA design shows improved back-off efficiency, but suffers linearity problem because the use of switching mode amplifier [6].

In this paper, a 60-GHz Class AB power amplifier with efficiency enhancement at power back-off is proposed. A transformer based power combining architecture is used to enlarge output power of the PA. It enables the control and access to individual amplifiers in the power combined amplifier, which improves efficiency at power back-off [7]. Section II shows the Class AB can achieve higher back-off efficiency with no compromise in linearity. Furthermore, power gain and reverse isolation of the transistors are limited in millimeter wave frequencies. This is because of the parasitic negative feedback path caused by  $C_{gd}$ , which also involves in unstable issue [1]. Thus, a neutralization technique is used, which improves the power gain and stability of the amplifiers.

## II. PA DESIGN DESCRIPTION

### A. Unit PA Design

Fig. 1 shows the schematic of the unit PA. Four unit PAs are used to realize power combining. The transistors M1 and M2 are biased into Class AB condition by the center tap of the input transformer, as indicated in Fig. 2. Many power combining PA papers utilize switching mode unit PAs, like Class C, Class E or Class F [5][6][10][11]. This makes the unit PAs have higher efficiency, compared with classical controlled conduction angle amplifiers. Nevertheless, the switching mode amplifiers suffer from bad linearity and gain behaviour, which is substantial for high-gain and high peak-to-average power ratio (PAPR) application. Thus, the controlled conduction angle amplifier of Class AB unit amplifiers are utilized in the proposed design. Compared to other controlled conduction angle amplifier structure, like Class A and Class B, the PA operating in Class AB shows better efficiency with no compromise in linearity.

The unit PAs utilize the differential-in-differential-out structure, which has much better common mode rejection ratio (CMRR) compared to single-ended structure. In order to neutralize the parasitic negative feedback path caused by  $C_{gd}$  of M1 and M2 in Fig. 1, the neutralization technique is implemented by cross-connecting the interdigitated capacitors  $C_{neu}$  between the drain and gate terminals of M1 and M2 (see Fig. 1) [1][12].

Each unit PA can be turned off individually by making the control voltage of M3 to be  $V_{DD}$ . Several PAs can be deactivated when system is used in low-power mode operation. This technique can make sure the PA design still have a good efficiency at power back-off.

### B. Power Combining

In order to implement power combining for output power improvement, passive structures can be utilized. Traditionally, output power can be combined in phase using the Wilkinson structure. Multiple two-way Wilkinson structures can be utilized to combine 4 or 8 PAs, but the insertion loss of the combining network will soon be greater than the added power of additional amplifiers. Also, the interconnections and mismatches introduced by these interconnections will degrade the overall performance [8][9]. Alternatively,  $\lambda/4$  transmission line can be employed to combine power but without the ballast resistor [8][10][11].

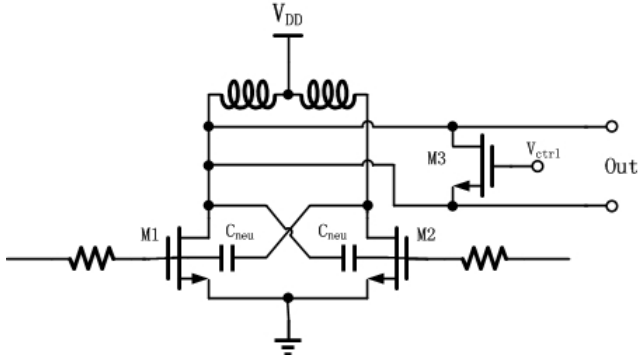


Fig. 1. Schematic of a unit PA.

The proposed PA utilizes transformer to combine output power, which makes the design very compact [8]. Furthermore, the current-voltage mode combining architecture is utilized to demonstrate a higher power transfer, compared with conventional current- or voltage-combining architecture. Meanwhile, since four unit differential-input PAs are targeted to combine together, the T-lines based splitter-balun is utilized to split the input power. The co-designed balun with the splitter is to improve the inter-path isolation and also transfer single-ended input signal to differential signal [2]. The simplified schematic of the designed 65-nm CMOS 60-GHz PA is showed in Fig. 2.

The main issue of balun design to implement power splitting and combining is to perform a high coupling coefficient ( $k$ ) with a minimum of insertion loss ( $IL_m$ ). The proposed balun uses stacked coupling structure, which exhibits better performances in terms of coupling and area consumption compared to planar coupling based baluns. The coupling is performed with the top metal levels that form the primary and the secondary, respectively,

$$k = \sqrt{\frac{\Im(Z_{12})\Im(Z_{21})}{\Im(Z_{11})\Im(Z_{22})}} \quad (1)$$

$$IL_m = -10 \cdot \log_{10}(1 + 2(x - \sqrt{x^2 + x})) \quad (2)$$

where

$$x = \frac{\Re(Z_{11}) \cdot \Re(Z_{22}) - [\Re(Z_{11})]^2}{[\Im(Z_{12})]^2 [\Re(Z_{12})]^2} \quad (3)$$

In order to completely characterize the transformer as a balun, amplitude and phase imbalances must be evaluated. These parameters can be evaluated using CMRR, which can be computed following (4),

$$CMRR = \left| \frac{S_{31} - S_{21}}{S_{31} + S_{21}} \right| \quad (4)$$

At millimeter-wave frequencies, the CMRR is usually poor because of the high capacitive coupling between the primary and the secondary of the transformer. Thus, a high quality factor metal-insulator-metal (MiM) capacitor  $C_{in}$  is connected to the end of the primary, as shown in Fig. 2 [2].

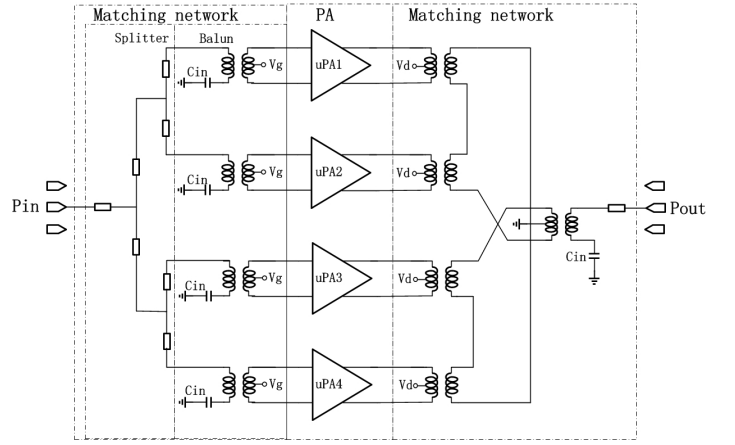


Fig. 2. Simplified schematic of the designed 60-GHz PA.

With the power-combing technique, each unit amplifier can be turned on or off as the required output power varies, controlled by a digital code (Fig. 2). At the peak output power, each unit amplifier is on (assume the corresponding peak input power and load seen by each amplifier is  $V_{i,max}$  and  $1/4 \cdot R_L$  respectively). The efficiency of each amplifier, as well as the power combined amplifier, reaches maximum:

$$\eta_{overall} = \eta_{unit} = \eta_{max}. \quad (5)$$

When power is at 6dB back-off, the output swing of each individual amplifier is  $1/2 \cdot V_{o,max}$ . Thus, the efficiency of each amplifier as well as the overall efficiency of the power combined amplifier drops. However, if uPA1 and uPA3 turned off, the output swing of each individual amplifier returns to the maximum value of  $V_{o,max}$  as derived in [7]. Thus, the efficiency can still reaches its maximum following (5). When power is 12dB back-off, only uPA4 is turned on. In this condition, the effective load seen by each amplifier is

$$R = R_L. \quad (6)$$

This is because the effective voltage as well as the effective current on the load halves. Similarly, the efficiency can still reaches its maximum following (5). Fig. 3 shows the efficiency of proposed PA with ideal power combining transformer.

### III. CONCLUSION

A 60-GHz power amplifier with efficiency enhancement at power back-off is proposed based on 65-nm CMOS technology. The input signal is splitted into four way by T-lines based splitter. After amplified by four differential unit PAs, the output power is combined by current-voltage mode power combining transformers. Thus, the high output power is implemented using power combining technique. Furthermore, each individual unit PA can be turned off separately, which implements efficiency enhancement at power back-off.

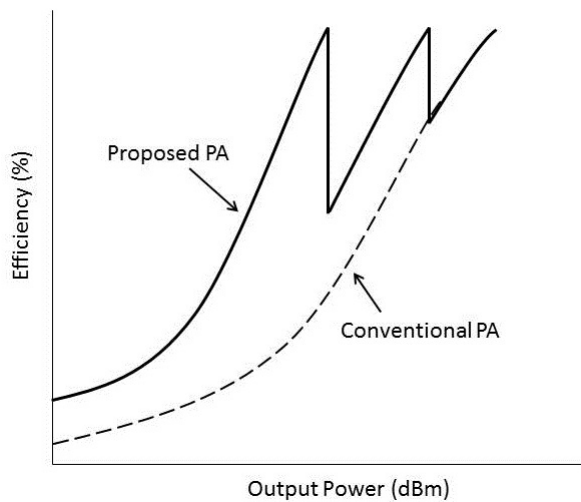


Fig. 3. Comparison of efficiency between the PA based on proposed power combining technique and the conventional PA.

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