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A Fully Integrated GaN Dual-Channel Power Amplifier With Crosstalk Suppression for 5G Massive MIMO Transmitters

G. Reza Nikandish, Senior Member, IEEE, Robert Bogdan Staszewski, Fellow, IEEE, and Anding Zhu, Senior Member, IEEE

Abstract—We present a broadband dual-channel power amplifier (PA) with crosstalk suppression for multi-input multi-output (MIMO) communications. Operation of MIMO system with crosstalk is theoretically evaluated for two popular coding schemes including the space-time coding and linear precoding. Design challenges of a multi-channel PA on a single chip are investigated and circuit techniques, including second-harmonic trapping integrated into the output matching network and the use of back-via lines to isolate the channels, are proposed to mitigate the inter-channel crosstalk. A fully integrated dual-channel PA prototype, implemented using a 250-nm GaN-on-SiC process, provides 34.9–36.3 dBm output power, 44–49% power-added efficiency (PAE), 11.3–12.3 dB power gain, 31.0–34.2 dB second-harmonic rejection, and −28.1 dB to −25.7 dB inter-channel crosstalk across 4.5–6.5 GHz. For a 100-MHz 256-QAM signal with 7.2 dB peak-to-average power ratio (PAPR), the PA achieves 29.9 dBm average output power, 30% average PAE, −38.2/−39.1 dB adjacent channel leakage ratio (ACLR), and −28.2 dB (3.9%) rms error vector magnitude (EVM), without using digital predistortion (DPD). Effect of crosstalk on linearity of the dual-channel PA is also measured and it is shown that for a 256-QAM signal EVM can increase by 3–8 dB, depending on relative power levels of the two channels.

Index Terms—5G, broadband amplifier, crosstalk, GaN, multi-input multi-output (MIMO), power amplifier (PA), transmitter.

I. INTRODUCTION

The continuous growth in the demand for wireless connectivity has led to the emergence of the Fifth Generation (5G) wireless networks. A multi-input multi-output (MIMO) system is one of the key enabling technologies for 5G. MIMO can be used either in spatial diversity or spatial multiplexing mode. The spatial diversity can extend the coverage range by transmitting the same information over all transmitter (TX) antennas, while in the spatial multiplexing independent signals are simultaneously transmitted over the same frequency to increase spectral efficiency. Massive MIMO with a large number of TX and receiver (RX) antennas is used in 5G [1].

It is desired to integrate multiple TX and/or RX front-end channels on a single chip. Such integration provides numerous advantages including lower variations in performance of different channels, ease of system calibration, lowered fabrication costs, and compact hardware implementation [2].

Several integrated MIMO front-ends including transceivers and multi-channel power amplifiers (PAs) are reported in the literature [3], [4], [5]. Most of these circuits are implemented using mainstream silicon technologies to achieve low cost and high level of integration. However, these process technologies suffer from low output power levels, low efficiency, and high crosstalk between channels as a result of lossy substrate. GaN monolithic microwave integrated circuit (MMIC) technology is an attractive solution for 5G systems, especially for base-station PAs [6], [7], [8], where it can provide high output power levels in a compact chip area. Furthermore, the lower losses of its SiC substrate help to reduce crosstalk in a multi-channel PA, which has been shown to have the most detrimental effect on the performance of MIMO systems [5]. Although some crosstalk cancellation techniques have been developed for MIMO transmitters using digital a predistortion (DPD), e.g., [9], it is still essential to achieve high linearity and low crosstalk at the raw circuit-level implementation.

In this paper, we present design and implementation of a dual-channel monolithic GaN PA for 5G MIMO transmitters. The new contributions can be summarized as follows.

1) A crosstalk theory based on signal-to-noise ratio (SNR) is developed to benchmark performance of a 2×2 MIMO communication system for two popular coding schemes, Alamouti space-time coding [10] and linear precoding [11].

2) A crosstalk reduction technique is proposed for multi-channel PAs by embedding a broadband second-harmonic filter into the PA output matching network.

3) A line of back-vias available in monolithic GaN processes is used to mitigate the parasitic transformer coupling between the channels.

4) The crosstalk and its effects on the dual-channel PA performance are characterized using both continuous-wave and modulated-signal measurements, first time ever in the GaN process.

The paper is organized as follows. In Section II, design considerations for a single-chip multi-channel PA are presented. Design of the PA circuitry with harmonic filter is described in Section III. Finally, in Section IV, we provide single- and dual-channel measurement results.

II. MULTI-CHANNEL PA DESIGN FOR MIMO TX

A. Operation of MIMO System with Crosstalk

The block diagram of a 2×2 MIMO communication system is shown in Fig. 1. It is used as a demonstrator of the crosstalk...
issue in a practical multi-channel MIMO system. We derive the output SNR in terms of input SNR and the system parameters. The TX, RX, and the channel can be modeled by the matrices $[G_{TX}]$, $[G_{RX}]$, and $[H]$, respectively. Assuming symmetric TX channels, the TX system can be modeled by a direct gain of $g_t$ and a coupled gain of $\alpha_t$. Similarly, the RX system can be modeled by parameters $g_r$ and $\alpha_r$. The system can be modeled by an equivalent channel matrix of

$$[H_e] = \begin{bmatrix} 1 & \alpha_t \\ \alpha_t & 1 \end{bmatrix} \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} 1 & \alpha_r \\ \alpha_r & 1 \end{bmatrix}. \tag{1}$$

The physical channel matrix $[H]$ is practically determined for specific propagation conditions. Assuming a lossless symmetric channel, we use the following model

$$[H] = \begin{bmatrix} \sqrt{1 - k^2} & k e^{-j\theta_h} \\ k e^{-j\theta_h} & \sqrt{1 - k^2} \end{bmatrix}, \tag{2}$$

where two parameters $0 \leq k \leq 1$ and $0 \leq \theta_h < 2\pi$ can be used to investigate the effect of channel behavior on the MIMO system with crosstalk. The parameter $k$ indicates the strength of correlation between the two channels. A case of $k = 0$ refers to two uncorrelated single-input single-output (SISO) channels. Moreover, the parameter $\theta_h$ captures a relative phase shift between the main and cross paths. To proceed, we consider two popular coding schemes, Alamouti space-time coding [10] and linear precoding [11], and derive the SNR loss due to crosstalk.

1) Alamouti Space-Time Coding: Assuming the Alamouti space-time coding scheme with a maximum likelihood detector, the received signal matrix $[R]$ is given by

$$[R] = [H_e][S] + [N], \tag{3}$$

where $[S]$ denotes the transmitted signal matrix and $[N]$ is the additive channel noise matrix. The TX crosstalk has the most detrimental effect on the quality of detected signal [5]. By neglecting the RX crosstalk ($\alpha_r = 0$), and considering the TX crosstalk as $\alpha_t = |\alpha_t|e^{-j\theta_h}$, it can be shown that the SNR loss due to the crosstalk is derived as follows

$$\Delta SNR = -10\log_{10} \left( 1 + |\alpha_t|^2 + 4|\alpha_t||k\sqrt{1 - k^2}\cos\theta_h\cos\theta_t| \right). \tag{4}$$

In the case of $k = 0$, the crosstalk should be lower than $-6.6$ dB to limit the SNR loss to 0.2 dB. The maximum SNR loss condition can be derived from $\partial(\Delta SNR)/\partial k = 0$, which leads to $k = 1/\sqrt{2}$. Using this value and $\cos\theta_h = \cos\theta_t = \pm 1$ in (2), the maximum SNR loss is given by

$$\Delta SNR_{\text{max}} = -20\log_{10} (1 + |\alpha_t|). \tag{5}$$

This is shown in Fig. 2, which indicates that $< -16.3$ dB crosstalk is required to maintain the SNR loss $< 0.2$ dB.

2) Linear Precoding: In the case of linear precoding with matched filter, the received signal is given by

$$[R] = [H]^H[H_e][S] + [N], \tag{6}$$

where precoder matrix $[H]^H$ is the Hermitian (conjugate transpose) of the physical channel matrix. It can be shown that the SNR loss due to the TX crosstalk is derived as

$$\Delta SNR = -10\log_{10} \left( \frac{|\alpha_t + \beta|^2 + 1}{|1 + \alpha_t|\beta|2(1 + \beta^2)|} \right), \tag{7}$$

where $\beta = 2k\sqrt{1 - k^2}\cos\theta_h$. The maximum $\Delta SNR$ is reached for $k = 1/\sqrt{2}$, $\cos\theta_h = \pm 1$, and $\cos\theta_t = \mp 1$ as

$$\Delta SNR_{\text{max}} = -10\log_{10} \left( \frac{1 - |\alpha_t|^2 + 1}{2(1 - |\alpha_t|^2)} \right). \tag{8}$$

This is shown in Fig. 2, indicating $< -13.6$ dB crosstalk requirement to achieve the SNR loss lower than 0.2 dB.

The loss of SNR increases bit error rate (BER) of the detected signal. Theoretically, assuming that the error power spectral density is represented by additive white Gaussian noise (AWGN) and uniformly distributed among all constellation points, for example for 64-QAM and 256-QAM signals, SNR should be respectively 15 dB and 19 dB to achieve an average BER of $10^{-3}$ [12]. In practice, AM-AM and AM-PM distortions of the PA lead to larger errors at larger constellation points. Some theoretical and experimental investigations of the TX crosstalk effects on the MIMO system performance suggest an isolation requirement of roughly 20 dB for negligible performance degradation [5], [9], [13]. However, more accurate modeling and analysis are yet required for high-order and wideband modulation schemes used in 5G networks.

B. Circuit Techniques for Multi-Channel PA

It is desirable to integrate two or more PAs on a single chip to reduce the system cost and size. There are two major mechanisms of crosstalk in a dual-channel PA chip shown in Fig. 3. 1) coupling between metal traces in the matching networks of the two PAs, and 2) coupling through the substrate which can be modeled by a distributed resistive-capacitive network. It should also be mentioned that, in practice, there...
is substantial coupling between TX channels through the antenna networks. Although such antenna couplings cannot be mitigated using the on-chip circuit techniques, it should be considered in the MIMO TX crosstalk discussed.

We use two techniques to mitigate the substrate coupling. 1) Since the substrate coupling increases with frequency, crosstalk would be higher at harmonic frequencies (Fig. 3). Harmonic components coupled through the substrate not only degrade the linearity of the other channel, but also can be added to its harmonic contents with an unwanted phase and reduce the efficiency. A second-harmonic filter can be embedded into the PA output matching network to suppress its second-harmonic components before reaching the other channel. 2) The parasitic transformer coupling can be reduced by providing a large layout space between the two PA circuits. In this design, a minimum spacing of 300 \( \mu \)m is applied, which leads to an inter-channel transformer coupling coefficient of \( k_{mm} < 0.06 \). Integrated GaN processes usually provide back-via through the substrate for grounding. This feature can be used to develop a shielding wall to reduce the substrate coupling (shown on chip micrograph in Fig. 4).

III. PA CIRCUIT DESIGN WITH HARMONIC FILTER

The PA is designed using a 250-nm GaN-on-SiC technology. The PA uses an 8 \( \times \) 125 \( \mu \)m gate-width transistor, with the drain supply voltage of 28 V, to be able to deliver 36 dBm output power. It is operated in the continuous class-B mode, where the extended design space for the optimum load impedance at the fundamental and second-harmonic frequencies helps to achieve high efficiency over a broad bandwidth [14]. In a narrow-band PA, the second harmonic could be readily suppressed at the output by incorporating a series or parallel resonant circuit into the matching network. In a broadband PA, however, this is a challenging task requiring trade-offs between bandwidth, insertion loss, and harmonic rejection in the output matching network. To this end, the output matching network is realized using a two-section minimum-inductance BPF with extra transmission zeros [8]. The circuit schematic of the two-channel PA is shown in Fig. 4, where a row of ground back vias is used to mitigate crosstalk arising from the substrate and parasitic transformer couplings. EM simulations indicate that this technique reduces the crosstalk by \( \sim 2–7 \) dB across 4.0–7.0 GHz band.

The transistor gate bias exhibits significant effects on AM-AM and AM-PM distortions of the PA. In this design, a gate bias of –2.4 V is chosen to mitigate nonlinearity of the transistor’s transconductance and gate-source capacitance [7].

The PA delivers 35.4–36.4 dBm output power, 47–54\% drain efficiency (DE), 44–50\% PAE, and 11.4–12.4 dB power gain across 4.5–6.5 GHz. These results are achieved at 24 dBm input power. AM-AM and AM-PM are respectively 1.4 dB and 0.9 dB, up to 36.2 dBm output power at 5.0 GHz.

IV. MEASUREMENT RESULTS

The PA is implemented using the 250-nm GaN-on-SiC process from WIN Semiconductors. The chip micrograph is shown in Fig. 4. The chip is mounted on the test PCB, and its bias and RF pads are wire-bonded to the PCB traces. The PA is characterized in single- and dual-channel operation modes using continuous-wave and modulated signals.

A. Single-Channel Measurements

The PA is biased at \( V_{GS} = –2.4 \) V and \( V_{DS} = 28 \) V, consuming 17 mA bias current. Measured output power, gain, DE, PAE, and second-harmonic rejection ratio (HRR2) versus frequency are shown in Fig. 5. The PA achieves 34.9–36.3 dBm output power, 11.3–12.3 dB gain, 48–52\% DE, 44–49\% PAE, and 31.0–34.2 dB HRR2 across the 4.5–6.5 GHz band. These results are measured at the input power of 24 dBm and 3–4 dB gain compression.

In Fig. 6, output constellation and spectrum of a single PA channel are shown for a 100-MHz 256-QAM signal with 7.2 dB PAPR at 5.0 GHz. The input power is adjusted to achieve EVM \( < –28 \) dB. The average output power, DE, and PAE are respectively 29.9 dBm, 33\%, and 30\%, while EVM is measured as –28.2 dB (3.9\%). Also, adjacent channel leakage ratio (ACLR) of the output spectrum is –38.2/–39.1 dBc. By applying a DPD with an iterative learning control technique [15], EVM and ACLR can be respectively improved to –47.3 dB (0.43\%) and –47.5/–47.9 dBc.

In Fig. 7, EVM, average DE, and ACLR are shown versus average output power for modulation bandwidths of 50 and
Fig. 5. Measured output power, gain, DE, PAE, and HRR2 versus frequency, at input power of 24 dBm.

Fig. 6. Measured output constellation and spectrum for a 100-MHz 256-QAM 7.2-dB PAPR signal at 5.0 GHz. The output signal features 29.9 dBm average power and 5.6 dB PAPR.

100 MHz. Measured EVM is about 4 dB lower for the 50-MHz bandwidth in linear operation, but the difference becomes narrower as the output power increases. ACLR is slightly lower for the 50-MHz bandwidth, while average efficiency is almost the same for the two cases. EVM < -32 dB can only be achieved for 50-MHz 256-QAM signal with 29.8 dBm average output power and 29.5% average DE.

B. Dual-Channel Measurements

To measure the crosstalk between the two PA channels, the input power is applied to one of the channels ($P_{in1}$). Then, the direct output power in the same channel, $P_{out1} = G_{11}P_{in1}$, and the coupled output power in the second channel, $P_{out2} = G_{21}P_{in1}$, are recorded. This is a simplified approach to measure the crosstalk $G_{21}/G_{11}$ using only one signal source. This measurement can capture nonlinearities in $G_{11}$ and $G_{21}$, but excludes mutual nonlinearities, i.e., dependency of $G_{11}$ and $G_{21}$ on $P_{in2}$, are usually second-order effects. Such mutual nonlinearities can be measured using a setup with two independent sources.

In Fig. 8, the measured crosstalk is shown versus output power. The crosstalk reads within $-30.3$ dB to $-28.5$ dB in low-power operation (0 dBm input) and $-28.1$ dB to $-25.7$ dB in high-power operation (24 dBm input). It is noted that $<-25$ dB crosstalk can be achieved which meets the requirements theoretically derived in Section II and the $-20$ dB limit suggested in the literature.

Fig. 7. Measured EVM, average DE, and ACLR versus average output power for a 50/100-MHz 256-QAM 7.2-dB PAPR signal at 5.0 GHz (w/o DPD).

Fig. 8. Measured crosstalk between the two PA channels versus frequency at low/high input power levels.

Test setup shown in Fig. 9 is used to measure the effect of crosstalk on the quality of modulated signals. The relative input power level to the two PA channels is varied using a 1-dB step attenuator$^1$. The results are shown in Fig. 10 for a 50-MHz 256-QAM signal at 5.0 GHz. The EVM degrades as the input power to the other channel increases. The linear output power $P_{out, lin}$, defined as the maximum average output power level for EVM $<-28$ dB, is 30.2 dBm for a single-channel PA. However, it reduces to 29.7 dBm when both channels operate at the same power, i.e., $\Delta P_{in} = 0$ dB, and further degrades to 29.6/28.6 dBm for $\Delta P_{in} = 3/6$ dB. Therefore, the PA should be operated in a bit stronger back-off in order to achieve the required linearity in the presence of crosstalk.

In Table I, the performance of the proposed dual-channel PA is summarized and compared with published broadband inte-

$^1$A limitation of this test setup is correlation of the two modulated signals applied to the two PA channels. Two signal generators would be required to create the independently modulated signals, which was not available in this work. Furthermore, a phase shift should also be applied between the two inputs to represent the MIMO operation more accurately.
TABLE I
SUMMARY OF THE PROPOSED DUAL-CHANNEL PA AND COMPARISON WITH BROADBAND FULLY INTEGRATED SINGLE-CHANNEL GaN PAs

<table>
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<tr>
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<td>4.5–5.9</td>
<td>6.8–7.2</td>
<td>4.9–5.9</td>
<td>4.6–6.0</td>
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<td>37.7–38.0</td>
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<td>34.7–36.2</td>
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<td>Crosstalk (dB)</td>
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<td>\textit{f}_c (GHz)</td>
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<td>7.0</td>
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<td>EVM\textsubscript{avg} (dB)</td>
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<td>32</td>
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<td>P\textsubscript{o,avg} (dBm)</td>
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