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Design of Broadband Continuous Mode MMIC Power Amplifiers With Bandwidth Improvement

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Abstract— This paper presents the design of continuous mode monolithic microwave integrated circuit (MMIC) power amplifiers (PAs) with bandwidth improvement. The output matching network (OMN) satisfying the continuous mode in broadband can be efficiently constructed with LC resonant circuits. The bandwidth can be further improved through generating the new LC unit in OMN with a minimum number of components added possible. Two prototype MMIC PAs are demonstrated with 0.25- μm Gallium Nitride (GaN) MMIC process. The measured drain efficiency is over 39.2% and 38.7% from 4.5 GHz to 6.5 GHz, respectively. When driven by 100-MHz modulated signals, two PAs exhibit great linearity performance with adjacent channel leakage ratio lower than -51.2 dBc and -53.4 dBc with digital predistortion.

Index Terms— Broadband, continuous mode, Gallium Nitride, monolithic microwave integrated circuit (MMIC), power amplifiers.

I. INTRODUCTION

Driven by demands for higher data rates, radio frequency (RF) power amplifiers (PAs) in 5G are expected to operate in broadband with high efficiency. The continuous mode PA introduced in [1] is an attractive solution. To realize it, the output matching network (OMN) of the PA should provide required impedances at both the fundamental frequency and harmonics simultaneously. In hybrid designs using microstrip lines, such OMNs are usually in large sizes [2], [3]. The base stations in 5G systems require high integration, compact PAs with high output power are desired. Gallium Nitride (GaN) materials offer high power density. The GaN monolithic microwave integrated circuit (MMIC) PA is thus a good candidate in this application.

In MMIC, the frequency-dependent behaviours of the OMN can be constructed with LC resonant circuits efficiently, since it can not only locate the harmonics but also generate equivalent frequency-dependent components [4]. But the bandwidth of the PA heavily relies on how well the frequency response of the circuits matches the desired impedance requirement. Complex optimization is often required.

This paper proposes some simple methods for PA's bandwidth improvement through generating new LC circuit elements with less complexity. Two MMIC PAs are implemented with 0.25- μm GaN HEMT process for demonstration.

II. BANDWIDTH IMPROVED CONTINUOUS MODE PA

A. Bandwidth Improvement Approaches

The fundamental impedance Z_{f_0} and the second harmonic impedance Z_{2f_0} in continuous Class-B mode are written as

$$Z_{f_0} = R_{opt} - j \cdot \delta \cdot R_{opt} \quad (1)$$

$$Z_{2f_0} = 0 + j \cdot \frac{3\pi}{8} \cdot \delta \cdot R_{opt} \quad (2)$$

where R_{opt} is the transistor's optimum load and δ varies in a range of $[-1, 1]$. The broadband continuous mode operation can be achieved when the variation of δ are properly mapped to the frequency response of OMN. Thus, δ becomes the function of frequency, and OMN is expected to provide frequency-dependent fundamental reactance $X_1(f) = -\delta(f)R_{opt}$ and second harmonic reactance $X_2(2f) = \delta(2f)R_{opt}3\pi/8$.

The bandwidth of the constructed OMN depends on how well its frequency response fit the δ variation at both frequencies, which is largely affected by the combination of LC circuits [4]. Poor fitting leads to bandwidth reduction or efficiency degradation in band. To realize valid harmonic control, the minimum number of LC circuits used is two. The bandwidth can be improved when adding more components to OMN. However, this would increase the circuit complexity.

To improve the fitting with less number of components, a new LC unit can be generated from the existing component in OMN. The components forming LC circuits have bigger impact on bandwidth. Among them, there exist the sensitive component whose variation in component value brings larger impact to OMN's frequency response. The impact of individual components can be detected through Monte Carlo simulation. Then, δ fitting can be improved if the sensitive component is modified to a new LC circuit, generating a new frequency-dependent component. Since the added component should not change the previous reactance at the fundamental frequency and second harmonic, the original resonance frequency should be guaranteed after adding the new component.

Another way of generating a new LC circuit is utilizing the single component in OMN. Besides LC circuits, there are other single components needed in OMN to function properly. If such component can be modified to a LC resonant circuit, the OMN with two LC units is upgraded to the one with three LC units. By assigning the resonance frequency properly, δ fitting and the bandwidth performance can be improved.

B. OMN Construction

Two OMNs are demonstrated with 0.25- μm GaN HEMT process. The transistor size is $6 \times 125 \mu\text{m}$, and it is biased at $V_D = 28 \text{ V}$ and $V_G = -2.4 \text{ V}$. Under this condition, transistor's optimal impedance at the intrinsic plane is $R_{opt} = 120 \Omega$. The operating frequency ranges from 4.5 GHz to 6.5 GHz.

Fig. 1. The proposed OMN topologies with improvement, (a) Circuit 1 and (b) its simulated frequency response normalized to R_{opt} (δ range [-0.55, -0.1]), (c) Circuit 2 and (d) its simulated frequency response normalized to R_{opt} (δ range [-0.55, -0.1]).

The OMN can be constructed with two LC resonant circuits initially using the approach proposed in [4]. Fig. 1(a) and Fig. 1(c) illustrate two possible OMN built with two LC units, which are Circuit 1 and Circuit 2, respectively. Both circuits utilize the drain parasitic capacitor C_{out} and the drain bias inductor L_b to form the first resonant circuit, whose resonance frequency f_{1r} locates between the fundamental frequency and the second harmonic. Circuit 1 adopts the series LC resonating at second harmonic, while Circuit 2 adopts the parallel one resonating at fundamental frequency. Besides, both circuits place the DC block capacitor and an inductor in series with the load. In this way, equivalent frequency-dependent components generated from LC circuits form the fundamental impedance with inductive reactance $X_1(f)$ and the capacitive reactance $X_2(2f)$. Once the OMN topology is decided, the optimal component values can be obtained from the multi-objective Bayesian optimization algorithm [5].

The component can be added for improvement. In the two cases, different approaches are adopted. For Circuit 1, the Monte Carlo simulation is used to detect the sensitive LC component. The result shows the frequency response is very sensitive to C_1 . Therefore, L_3 is added in parallel with C_1 . The resonance frequency of this new LC unit is lower than $2f_0$, and $f_{2r}=2f_0$ should be guaranteed to maintain the previous reactance at both frequencies. For Circuit 2, another capacitor C_2 is added in parallel with L_2 to build a new LC unit with resonance frequency f_{3r} equal to the second harmonic. Thus, it maintains the previous fundamental matching and helps to create better fitting at the second harmonic. Table I summarizes the optimal value given by the Bayesian optimization before and after adding the new component. The improvement of the frequency response is compared in Fig. 1(b) and Fig.

TABLE I
THE OPTIMAL COMPONENT VALUES

Variable	Circuit 1		Circuit 2	
	Without L_3	With L_3	Without C_2	With C_2
f_{1r} (GHz)	6.78	7.00	6.95	7.03
L_b (nH)	1.45	1.36	1.38	1.35
f_{2r} (GHz)	12.21	12.27	5.49	5.04
f_{3r} (GHz)	-	-	-	9.11
L_1 (nH)	1.70	0.56	2.34	2.00
L_2 (nH)	1.84	1.53	1.62	0.71
L_3 (nH)	-	3.00	-	-
C_1 (pF)	0.10	0.35	0.46	0.50
C_2 (pF)	0.27	0.30	-	0.43
C_3 (pF)	-	-	0.29	0.34

1(d) for both circuits, respectively. As can be observed, the fitting of the fundamental and second harmonic resistance are both improved after adding one more LC unit.

III. CIRCUIT IMPLEMENTATION AND MEASUREMENTS

To validate proposed approaches, two MMIC PAs, which are PA1 and PA2, adopting OMN topologies in Fig. 1(a) and Fig. 1(c) are demonstrated. When transferring lumped components to MMIC, the losses and parasitics of MMIC components need to be considered. Some inductors in OMN are replaced with transmission lines since the behaviour of MMIC spiral inductors approximates that of transmission lines. While for relatively large inductors, MMIC spiral inductors are still used to save the chip area. In both PAs, the input matching network is designed based on the source-pull simulation, and the stability circuit made of R_s and C_s is added to prevent oscillation. Bypass capacitors are placed near DC sources. The circuit layout has significant impact on the final performance, especially the broadband. Thus, necessary optimizations and adjustments are conducted.

The circuit schematic and chip photograph of two MMIC PAs are shown in Fig. 2. The fabricated chip is mounted on a PCB fixture with bonding wires. The input signal is generated from the vector signal generator, and then boosted by a driver PA. The output signal is measured with a spectrum analyzer, and the attenuator is used to protect the spectrum analyzer.

The measured drain efficiency (DE) and gain of both MMIC PAs are illustrated in Fig. 3. For comparison, the electromagnetic simulation results are also presented. Inside the 2 GHz bandwidth, the measured DE for PA1 is 39.2%-51.2%, and that of PA2 is 38.7%-50.6%. At power saturation, the measured power gain ranges from 7.8-10.4 dB for both PAs. The measurement results show good approximation to the simulation for both MMIC PAs.

To evaluate the linearity performance, two MMIC PAs are tested with 100-MHz OFDM signals at 5 GHz, 5.5 GHz and 6 GHz respectively. Digital predistortion (DPD) is applied to linearize MMIC PAs. The measured output signal spectra are presented in Fig. 4. The average output power of PA1 is 25.6-28.4 dBm with 26%-28.6% average efficiency, and PA2 achieves 25.9-28 dBm average power and 26.2%-29.5% average efficiency. After conducting DPD, the adjacent

Fig. 2. The circuit schematic and chip photography of (a) PA1 designed with Circuit 1 as the OMN and (b) PA2 designed with Circuit 2 as the OMN.

Fig. 3. Measured DE and gain versus frequency of (a) PA1 and (b) PA2; measured DE and gain versus output power at 5.5 GHz of (c) PA1 and (d) PA2.

channel leakage ratio (ACLR) is lower than -51.2 dBc and -53.4 dBc, respectively. The demonstrated PAs exhibit excellent linearity performance with modulated signals.

IV. CONCLUSION

This paper proposes two bandwidth improvement techniques for broadband continuous mode operation. Through analysing the OMN topology constructed with LC resonant circuits, the impedance fitting and the bandwidth is improved by adding minimum component possible. Two MMIC PAs

Fig. 4. Spectra plots with 100-MHz LTE signal for PA1 at (a) 5.0 GHz (b) 5.5 GHz (c) 6.0 GHz, and for PA2 at (d) 5.0 GHz (e) 5.5 GHz (f) 6.0 GHz with and without DPD.

are demonstrated with 0.25-um GaN process, achieving high efficiency and good linearity across 2 GHz bandwidth.

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