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A Novel 2.6-6.4 GHz Highly Integrated Broadband GaN Power Amplifier

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Abstract—In this letter, a novel methodology to achieve output broadband matching is proposed. Based on this methodology, a broadband GaN power amplifier with input matching and stabilization circuit integrated on-chip is designed. The implemented PA achieves a maximum drain efficiency of 62% to 79.2% from 2.6 GHz to 6.4 GHz (84.4% fractional bandwidth), with a saturated output power (Psat) of 34.3 to 35.8 dBm, while providing a gain larger than 10 dB. When tested with 802.11ac VHT80 MC9 (80MHz, 256-QAM) with 11.3 dB peak-to-average power ratio, PA achieves a drain efficiency of 22.1% to 25.2% with an average output power of 23 to 25.4 dBm across the whole band, while meeting the standard specification of EVM below -32 dB.

Index Terms—Broadband, highly integrated, gallium nitride (GaN), power amplifier.

I. INTRODUCTION

BROADBAND power amplifiers (PAs) with high efficiency have recently drawn much attention in multi-standards and broadband wireless communication systems. Since a high electron mobility GaN transistor exhibits high breakdown voltage and high power density, there is increasing interest and effort to design broadband PAs using this technique. To date, broadband GaN power amplifiers have been proposed in literature using distributed configurations [1]–[3] and various matching techniques such as reactive filter synthesis and real time frequency techniques [4]–[7]. A distributed PA has prominent advantages in the performance of return loss and wideband, however, it inherently suffers from low power efficiency and large size, making it unsuitable for low cost and low power application [1]. Compared with distributed PAs, the PAs using broadband matching techniques have better efficiency, however, the performance will be limited when the bandwidth of interest is larger than an octave [4]. In addition, the broadband matching networks are usually implemented using transmission line stubs on a PCB, resulting in high complexity and large PCB size. Thus, from practical

Fig. 1. (a) Optimum impedance and load impedance of proposed matching network (b) PAE contours at different frequency

perspective, design of broadband PAs with low cost and small size remains a challenge.

In this letter, a novel compact broadband output matching network and its design methodology are proposed. In this work, the operating band is divided into two sub-bands, and perfect output matching is targeted at the center frequency of these two sub-bands simultaneously. Besides, the load impedance of the output matching network does not deviate significantly from the required impedance at other frequencies in the giving band, and consequently a broadband performance is achieved. Based on this methodology, a highly integrated GaN PA operating from 2.6 GHz to 6.4 GHz is designed. The proposed PA delivers high efficiency with very small size, and thus can potentially be used in wireless communication systems including radars, WiFi, WiMax and instrumentation systems.

II. DESIGN OF BROADBAND OUTPUT MATCHING NETWORK

Based on the required saturated output power level of 35 dBm, the transistor's total gate width is set at 0.8 mm, and this GaN device can deliver saturated output power of 36.6 dBm under a drain voltage of 28 V.

In this work, we divide the whole band from 2.6 GHz to 6.4 GHz into two sub-bands with the center frequency of the lower and upper half band at 3.6 GHz and 5.7 GHz, respectively. In order to extract broadband performance, two objectives of output matching network need to be fulfilled. Firstly, perfect output impedance matching should be achieved at two center frequencies of 3.6 GHz and 5.7 GHz simultaneously. Secondly, the load impedance of matching network to be designed should not deviate significantly from the optimum impedance within the giving band, in order to avoid performance degradation in the band and maintain a continuous performance, which is the most significant

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Fig. 2. Schematic of the proposed PA

Fig. 3. Load impedance of output matching network at: (a) 5.7 GHz (b) 3.6 GHz

Fig. 4. Photo of GaN die and PCB

difference from the previous dual-band PAs [8], [9]. The design procedure of output matching network based on these two objectives is present as follows.

During the design, the performance of efficiency and output power are analyzed using load-pull simulation. Fig.1(a) shows the desired impedance from 2.6 GHz to 6.4 GHz. As observed, the real part of the required impedance at 5.7 GHz is 46Ω , and which is assumed to be 50Ω in order to facilitate output matching design. Correspondingly, only the imaginary part of the impedance is need to be considered at 5.7 GHz. With the consideration of low loss and compact size, the number and size of components to be utilized in matching network should be minimized. Hence, a novel compact matching network consisting of only three components is introduced: a series inductor L_1 , capacitor C_1 and one short-circuit stub TL_1 with electrical length θ of $\lambda/4$ at 5.7 GHz, as shown in Fig.2. At 5.7 GHz the TL_1 serves as an RF choke, and the inductor L_1 provides the required reactance together with the capacitor C_1 . The load impedance Z_L shown in Fig.3(a) is

$$Z_L = 50 + j(\omega L_1 - \frac{1}{\omega C_1}) \quad (1)$$

Setting imaginary part of Z_L to the required value, the relationship between the value of L_1 and C_1 can be defined. The final value of these two component will then be derived by the required impedance at 3.6 GHz.

Fig. 5. Measured S11 and S21

Fig. 6. Performance of the PA (a) Measured Psat and DE versus frequency (b) Measured output power and DE versus Pin at 2.6, 4.6 and 6.4 GHz

Fig. 7. Measured output power and DE with 802.11ac standard signals

Fig. 8. Measured spectrum, constellation and EVM at 5.4 GHz

At 3.6 GHz, the short-circuit TL_1 is equivalent to an inductor, and is included in the matching network, shown in Fig.3(b). In this case, the load impedance Z_L can be derived as follows,

$$Z_L = j\omega L_1 + \text{Re}(Z_A) + j \text{Im}(Z_A) \quad (2)$$

where,

$$\text{Re}(Z_A) = \frac{50Z_0^2 \tan^2 \theta}{50^2 + (Z_0 \tan \theta - \frac{1}{\omega C_1})^2} \quad (3)$$

$$\text{Im}(Z_A) = \frac{Z_0 \tan \theta (\frac{1}{\omega^2 C_1^2} - \frac{Z_0 \tan \theta}{\omega C_1} + 50^2)}{50^2 + (Z_0 \tan \theta - \frac{1}{\omega C_1})^2} \quad (4)$$

, where Z_0 and θ are the characteristic impedance and electrical length of the TL_1 at 3.6 GHz. Based on the required impedance at 3.6 GHz and the imaginary part of the required impedance at 5.7 GHz, Z_0 , L_1 and C_1 can be derived as 46.9Ω , 2.1 nH and 1.2 pF . The simulated load impedance of the proposed matching network is depicted in Fig.1. It can be observed that the impedance matches perfectly at 3.6 GHz and 5.7 GHz. The worst case for output matching occurs at 2.6 GHz, and such that the load impedance is located within -6% PAE contour, as shown in Fig.1(b). In practice, a decrease in 6% efficiency can

TABLE I
PERFORMANCE COMPARISON BETWEEN THE PROPOSED PA AND OTHER PAs

Ref.	This work	[1]	[2]	[3]	[6]	[10]	[11]
Freq (GHz)	2.6-6.4	2-6	0.5-6.5	1.5-10	2-6	2-6.5	2-6
Psat (dBm)	34.3-35.8	40.9-41.5	33.45	30.7	17.8-20.4	31-32	38.5-40
Efficiency (%)	DE:62-79.4	PAE:27-34	PAE:38	PAE:44	DE:19-28.4	PAE:31.4-51.5	PAE:25-30
Technology	GaN	GaN	GaN	GaAs	CMOS	GaAs	GaN
Die Size (mm ²)	1.3×0.9	4×1.9	2×2	2.15×2.15	0.57×1.57	3.7×2.6	6.3×3.75

be tolerated. Therefore, broadband performance can be realized by this proposed matching network.

III. IMPLEMENTATION AND MEASUREMENT

The PA was fabricated in Cree 0.25 μm GaN-on-SiC technology and bonded to the PCB implemented using RO4350 substrate with 20 mil thickness. Fig.4 depicts the photograph of the fabricated GaN die and PCB. The stabilization circuit consisting of R_0 , R_I and L_2 , and high-pass input matching circuit consisting of L_0 and C_0 were integrated on-chip, facilitating high integration of PA. Since bonding wire has lower loss and higher quality factor than an on-chip inductor, the inductor L_I is realized by utilizing a bonding wire with 1.3 mil diameter and 2.3 mm length. The transmission line was bent to extract compact size, and the core circuits on the PCB is within $6.5 \times 6.5 \text{ mm}^2$.

A gate voltage of -3 V is chosen for deep Class-AB operation based on the tradeoff between linearity and efficiency. Small signal S-parameters were measured to validate basic amplification function. The measured S-parameters are plotted in Fig. 5, indicating the PA has the small signal gain larger than 10 dB from 2.6 GHz to 6.4 GHz. PA was tested with continuous wave (CW) signal, and the measured results are reported in Fig.6. The PA achieves a drain efficiency of 62-79.4 % with a saturated output power between 34.3-35.8 dBm over the whole band.

The proposed PA's wideband performance is evaluated using the standard WLAN 802.11ac HT20 MCS7 (20 MHz, 64-QAM) and VHT80 MCS9 (80 MHz, 256-QAM) signals. As shown in Fig.7, when satisfying the standard specification of EVM<-32 dB for VHT80 MCS9, PA delivers an average output power of 23-28.5 dBm and achieves a drain efficiency of 22.5-37.8%. When tested with HT20 MCS7 signal, PA achieves a drain efficiency of 25.5-46% with an output power of 25.7-30.3 dBm, while meeting the standard specification of EVM <-28 dB. In addition, the measured constellation, EVM and spectrum at 5.4 GHz are depicted in Fig. 8. Finally, the comparison between the performance of this PA and published PAs is summarized [10], [11] in Table I.

IV. CONCLUSION

This work introduces a highly integrated broadband GaN power amplifier operating from 2.6 GHz to 6.4 GHz with compact size. The novelty of the proposed matching network to achieve broadband performance was verified by the measurement results. Large signal measurement result shows the PA achieves a drain efficiency higher than 60% with a

saturated power above 34.3 dBm over the whole band. Moreover, when tested with standard WLAN modulation signal, the PA exhibits high linearity. Due to its compact size, the proposed PA could be easily integrated in wireless communication systems.

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