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Design of a Dual-band Power Amplifier Using a Simple Method

Zhiwei Zhang, Zhiqun Cheng, *Member IEEE*, Vincent Fusco, *Fellow IEEE*, and Chao Gu

Abstract—This letter presents a simple method to design dual-band high-efficiency power amplifiers. The dual-band coupler is exploited to design the output circuits of the power amplifier. By proper selection of impedance conditions of terminal ports, the dual-band coupler can convert the fundamental impedance of transistor to the standard $50\ \Omega$ load at two frequencies. At the same time, the second harmonic impedance is also controlled without the need for additional tuning. For validation, a dual-band high-efficiency power amplifier is designed and fabricated by using CGH40010F GaN HEMT. Measurements indicate that the designed PA can deliver saturated output power of 41.6 dBm, 42.1 dBm at 1 GHz, 2.3 GHz, respectively. Also, the obtained drain efficiency exceeds 72% at both frequencies.

Index Terms— Dual-band, coupler, high-efficiency, power amplifier.

I. INTRODUCTION

For modern wireless communication technologies, RF front-end circuits often need to be able to support multi-mode and multi-frequency operation. As the key module of the wireless transmitter, the power amplifier (PA) naturally needs to follow this development trend. After years of development, many methods for designing multi-frequency and multi-mode PAs have been proposed [1-3]. One approach is to design reconfigurable circuits by using switches or diodes [1], which are not concurrent. Concurrent dual-band PAs also are presented by using dual-band matching technologies [2-4]. However, in [2-4], the harmonic tuning circuits and fundamental matching circuits have to be designed separately. Such design approach increases the complexity of designing PAs. Recently, the output circuit that supports two operation frequencies is achieved by using iterative optimization, such as real frequency technique (RFT) [5]. However, the optimization process is time consuming.

In order to achieve a dual-band high-efficiency PA more effectively, this letter proposes a simple design method. Here a dual-band coupler is used as the output circuit. By selecting proper terminal impedances of the coupler's four ports, the coupler can realize the conversion of impedances and harmonic control well at two frequency matching. For validation, a dual-

band high-efficiency PA with simple circuit topology is designed and fabricated.

II. ANALYSIS OF THE PROPOSED PAs

The schematic diagram of the dual-band coupler is shown in Fig. 1 [6].

Fig. 1. Schematic diagram of the dual-band coupler

In Fig. 1, the electrical lengths of all microstrip line are θ_0 at working frequency. Also, in Fig. 1, the Z_1 , Z_2 , Z_3 are the normalized characteristic impedance of microstrip lines, where the values of Z_1 , Z_2 , Z_3 are given as follows:

$$Z_1 = \sqrt{k - \sqrt{k^2 - 1}} \quad (1)$$

$$k = (2.5 + \sqrt{2}) + (1.5 + \sqrt{2})\cot^2\theta_0 \quad (2)$$

$$Z_2 = \frac{Z_1(Z_1^2 + \cot^2\theta_0)(1 + \sqrt{2})}{(1 - Z_1^2)} \quad (3)$$

$$Z_3 = \frac{Z_2}{\sqrt{2}} \quad (4)$$

This dual-band coupler can operate at two frequencies (f_1 and f_2) when the following relationships are satisfied [6]:

$$\theta_0(f_1) = \frac{\pi}{1 + \frac{f_2}{f_1}}, \quad \theta_0(f_2) = \frac{\pi}{1 + \frac{f_1}{f_2}} \quad (5)$$

By setting appropriate θ_0 at the desired band frequencies f_1 and f_2 , the dual-band coupler can be achieved. The ratios f_2/f_1 of 2.3 is taken in this paper.

Also, the S-parameters transfer matrix of the coupler can be expressed as [6]

$$S = -\frac{1}{\sqrt{2}} \begin{bmatrix} 0 & je^{j\Phi} & e^{j\Phi} & 0 \\ je^{j\Phi} & 0 & 0 & e^{j\Phi} \\ e^{j\Phi} & 0 & 0 & je^{j\Phi} \\ 0 & e^{j\Phi} & je^{j\Phi} & 0 \end{bmatrix} \quad (6)$$

where Φ can be given as

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$$\phi = \tan^{-1} \frac{2Z_0^3 \tan \theta_0}{\left(\frac{2}{(1+\sqrt{2})\cos^2 \theta_0} + 4 + 7\tan^2 \theta_0 \right) Z_0^2 - \tan^2 \theta_0} \quad (7)$$

where Z_0 is the load impedance of system impedance. Thus, the relationships between voltages and currents of the four ports can be obtained as follows:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = Z_0 \begin{bmatrix} 0 & -j\sqrt{2}e^{j\phi} & +je^{j\phi} & 0 \\ +je^{j\phi} & 0 & 0 & -j\sqrt{2}e^{j\phi} \\ 0 & +je^{j\phi} & -j\sqrt{2}e^{j\phi} & 0 \\ -j\sqrt{2}e^{j\phi} & 0 & 0 & +je^{j\phi} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \quad (8)$$

where V_1 , V_2 , V_3 and V_4 refer to the voltages at the port 1, port 2, port 3 and port 4, respectively. Similarly, I_1 , I_2 , I_3 and I_4 represent the currents flowing through the port 1, port 2, port 3 and port 4, respectively.

As shown in Fig. 2, the port 2 and port 4 are terminated to ground and open, respectively. Thus, the I_4 and V_2 are equal to zero. By using (8), several equations can be obtained as

$$V_3 = -Z_0 I_3 \quad (9)$$

$$I_3 = \sqrt{2} I_1 \quad (10)$$

$$V_1 = \sqrt{2} I_3 Z_0 \quad (11)$$

Then, the impedance seen by port 1 can be given as

$$Z_{port1} = \frac{V_1}{I_1} = \frac{\sqrt{2} I_3 Z_0}{I_1} \quad (12)$$

Substituting (9), (10) and (11) to (12), the following relationship can be obtained as

$$Z_{port1} = 2 \cdot Z_{port3} \quad (13)$$

It can be seen from (13) that the relationship between Z_{port1} and Z_{port3} does not depend on ϕ . In other words, regardless of the frequencies f_1 and f_2 , the coupler can convert the impedance Z_{port1} of port 1 to the impedance Z_{port3} of port 3, where Z_{port1} is always equal to $2Z_{port3}$. Thus, in this paper, the port 1 is used as the output terminal, and port 3 is used as the input terminal. In fact, in order to obtain different impedance conversion, the port 2 can be connected via a reactance to ground, which depends on the load impedance requirements of different PA modes. In practical design, the parasitic parameters of the transistor can be absorbed into the coupler only by slightly adjusting the parameters of the coupler.

Fig. 2. (a) The designed dual-band coupler with modified terminals. (b) Simulated frequency response of the designed coupler.

In [7], we propose a novel PA called hybrid class-EFJ PA. Its fundamental impedance Z_{f0} can be expressed as

$$Z_{f0} = (1 + j \cdot \gamma) \cdot R^* \quad (14)$$

where R^* represents the load impedance, which is from 15.89Ω to 46.29Ω . The γ is a coefficient taking a value of from -1 to 1. As we all known, the impedance of the output port 1 is usually standard 50Ω . Based on (13), the impedance of port 3 should be 25Ω , which means that the R^* of 25Ω in (14) should be taken. Thus, the coupler can match the load impedance of device to the standard 50Ω at two frequencies f_1 and f_2 .

Introduction of class-EFJ PA makes it possible to achieve fundamental impedance transformation in dual-band by using impedance conversion expressed in (13). By using (1)-(5), the parameters of dual-band coupler can be calculated at two frequencies f_1 and f_2 . The designed dual-band coupler with modified terminals is shown in Fig. 2 (a). The simulated frequency response of this coupler is shown in Fig. 2 (b). Seen from Fig. 2 (b), the frequency response indicates that the coupler can work well at 1 GHz and 2.3 GHz, respectively. In other words, this modified coupler can achieve fundamental impedance transformation at 1 GHz and 2.3 GHz. For high-efficiency PAs, the harmonic impedances should also be tuned carefully, like operating in [2-4]. In this letter, only the second harmonic is considered in the design process. With regard to the modified coupler, the total electrical length of the microstrip lines TL1, TL2 and TL3 is approximately 180° at 1 GHz, which is equal to 360° at the second harmonic frequency. Thus, the second harmonic impedance of the transistor's drain is zero. Due to the existence of the relationship shown in (5), the way this coupler controlling the second harmonic impedance at 1.0 GHz is also applicable to that at 2.3 GHz. Overall, this coupler can realize the functions of the output circuits of PAs at two frequencies, including the fundamental impedance conversion and the second harmonic impedance control. This concept is given in Fig. 3. In other words, we do not need to carefully tune the harmonics on the basis of dual-band fundamental matching well like the traditional, but only need to use this coupler to achieve the design of dual-band high-efficiency PAs, including the fundamental impedance conversion and the harmonic control at two frequencies. And dual-band harmonic control is inherently difficult. In this case, applying this coupler as the means for output circuit matching greatly simplifies the design of dual-band high-efficiency PAs.

Fig. 3. Concept of this work compared with the traditional.

III. IMPLEMENTATION AND MEASUREMENT

In order to validate the proposed method, a dual-band high-efficiency PA is designed using CGH40010F GaN HEMT, boarded on Rogers 4350B ($\epsilon_r = 3.66$, $H = 30$ mil). The bias voltages are 28 V and -2.8 V for the drain and gate, respectively. Parasitic parameters of devices should be included in the design process. The dual-band coupler including package parasitic parameters of transistor is designed as shown in Fig. 4 (a) [7]. The coupler shown in Fig. 4 (a) is obtained by optimizing on the basis of that of Fig. 2 (a). Due to the existence of parasitic parameters of the actual transistor, as shown in Fig. 4(a), the port 2 is no longer directly grounded, but grounded through a bias line. In practical situations, it may not be the best choice to connect port 2 directly to ground, but rather set it as a reactance. Naturally, other parameters of the coupler also need some minor adjustments. Fig. 4(b) displays the simulated impedance

of the designed coupler. It can be seen from Fig. 4(b) that the impedance of the designed coupler can satisfy the requirements of class EFJ PAs at two frequencies 1.0 GHz, 2.3 GHz. The impedances of the designed coupler with port 2 being ground and reactance are also shown in Fig. 4(b). Compared to such two conditions, the fundamental impedance of the designed coupler with terminalized reactance is closer to the load impedance of class-EFJ PAs at two frequencies 1.0 GHz, 2.3 GHz. Similarly, for the second harmonic frequency, the impedance of the coupler with reactance is closer to the short point than that with ground.

Fig. 4. (a) Designed circuits of PA with parasitic parameters (b) Simulated input impedance of the coupler with different terminals of the port 2 (c) simulated s11.

Regarding the design of the input circuit, wideband matching circuits covering from 1 GHz to 2.3 GHz is designed, whose effectiveness is proved by Fig. 4(c). Fig. 4 (c) shows that the value of s_{11} is smaller than -10 dB over the entire frequency band. A photograph of the fabricated PA and measurement setup is shown in Fig. 5. Power meter is used to measure the output power. The ACLRs can be obtained by a spectrum analyzer when the modulated signal is employed. Seen from Fig. 5, the larger size of this fabricated PA is mainly caused by the layout of dc bias lines. This can be completely solved by bending dc bias lines.

Fig. 5. The photograph of the fabricated PA and measurment set-up.

The performance of the PA is characterized by using continuous wave signals. Measurements are plotted in Fig. 6 and Fig. 7. As shown in Fig. 6, the PA can deliver saturated output power of 41.6 dBm and 42.1 dBm at 1.0 GHz and 2.3 GHz, respectively, with drain efficiency of 72.4% and 74.1%. At the same time, the gain of the PA are 11.6 dB and 11.2 dB at 1.0 GHz, 2.3 GHz, respectively. Fig. 7 displays the linearity of the designed PA. A 5MHz W-CDMA signal with peak-to-average ratio of 6.5 dB is exploited to drive the PA. The

measured ACLR are lower than -28.5 dBc, -29.4 dBc at 1.0 GHz and 2.3 GHz, respectively. Such measured ACLR results correspond to an average output power of about 35.7 dBm. Under this condition, drain efficiency of over 32% can be obtained.

Several PAs are listed in Table I for comparison. It can be seen from Table I that the designed PA has similar power, efficiency and gain at two frequencies compared to other PAs. RFT refer to Real frequency technique and requires iterative optimization. Harmonic tuning relies more on practical adjustments post manufacture. While the method proposed in this paper is the easiest to implement. These features illustrate the obvious difference between the proposed method and previous methods. It reveals that this work provides a simple and innovative way for the design and implementation of dual-band high efficiency PAs.

Fig. 6. Measured and simulated drain efficiency, gain and output power. (a) performances versus frequency (b) performances versus output power.

Fig. 7. Measured ACLR under 5MHz W-CDMA with 35.7 dBm average output power at two frequencies. (a) 1.0 GHz (b) 2.3 GHz.

TABLE I
PERFORMANCE COMPARISON WITH PAS

Ref	Method	Freq. (GHz)	Power (dBm)	Saturation DE (%)	Gain (dB)
[5]	Analysis and RFT*	2.35/3.45	40.6/41.2	70.3/71.4	10.6/11.2
[8]	Analysis and tuning	1.6/2.9	41.5/41.5	76/70	11/11
[9]	Harmonic tuning and RFT	2.6/3.5	42.4/41.1	76.7/72.8	11.5/10.5
[10]	MEMS	0.9/1.8	39.1/38.5	72.5/63.5	13.6/10.5
This Work	Coupler	1.0/2.3	41.6/42.1	72.4/74.1	11.6/11.2

IV. CONCLUSION

This letter presents a dual-band high-efficiency PA based on the dual-band coupler. A dual-band coupler is exploited to realize the output circuit of the PA. By properly setting terminal impedances, the designed coupler can transform the standard 50 Ω load to the required impedances of the transistor at two frequencies. For validation, a dual-band PA is implemented. Measurements show that the output power of 41.6 dBm, 42.1 dBm with over 72% drain efficiency can be obtained at 1.0

GHz, 2.3 GHz, respectively. It means that a novel and simple approach of designing dual-band PAs is provided.

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