Design of Broadband High-Efficiency Power Amplifier Based on Elliptic Low-Pass and Band-Pass Matching Network

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Abstract
A novel approach is proposed for the design of broadband and high-efficiency power amplifier (PA), with elliptic low-pass and band-pass filtering matching networks in this letter. Based on the equivalent circuit model of the GaN HEMT, the optimal topology of output matching network (MN) is designed as elliptic low-pass matching network with two attenuation poles, and the input MN is designed as band-pass matching network in the distributed form. A series of design procedure of the proposed topology is presented in detail. In this design, a 10-W GaN HEMT device (CGH44010F) was used. Results of measurement show that a broadband high-efficiency PA is realized from 1.45 to 2.55 GHz (fractional bandwidth = 55%) with measured drain efficiency of 70%–84% and output power of 40.4–42.4 dBm.

key words: Broadband amplifiers, GaN, high efficiency, power amplifier (PA), band-pass matching network, low-pass matching network.

Classification: Power devices and circuits

1. Introduction

The quick upgrade in the area of wireless communication brings great challenges for high-performance power amplifiers with higher output power, lower power consumption and wider bandwidth [1]. Consequently, a lot of research efforts have been made to enhance the performance of PA. To realize broadband and high-efficiency PA, the wideband Class-E [2], the Class-J [3], continuous Class-F (CCF) [4, 5] and continuous inverse Class-F (CCF–1) [6] modes are developed to achieve high-efficiency amplifications across wide bandwidth. Meanwhile, proper matching at both the fundamental and harmonics is required for these modes. In order to realize the above modes, a series of broadband impedance matching theories and techniques have been reported [7–11]. Particularly, classical filter design approaches are proved to be efficient [12–15]. For instance, the Cheby-

shev low-pass filtering (LPF) matching network (MN) were applied in highly efficient broadband PAs [16–19], in which low-pass topologies are frequently utilized. Nevertheless, limited by the inherent attribute of the low-pass type circuit topology, the PA incorporating low-pass matching networks cannot realized sharp roll-off transition falls out of the design band, and this inevitably decrease the power added efficiency (PAE) within the bandwidth. Furthermore, PAE becomes even worse when the highest frequency of the desired band (fH) is close to the second order harmonic of the lowest frequency of the band (2fL). Because the impedance values at fH and 2fL will be similar, which violates the load impedance requirement for harmonic tuned modes. [20] generates an attenuation pole between fH and 2fL to provide a swift impedance transition from fH to 2fL, which partly alleviates the problem. However, the matching network with only one attenuation pole is insufficient, in order to further restrain the second harmonic, more attenuation poles should be inserted without adding too much design complexity.

In this letter, a simple and effective method for the design of broadband high-efficiency PAs was proposed. An elliptic low-pass filter with two attenuation poles is proposed as output matching network (OMN) to further control the second harmonic. Meanwhile, a simple structure of band-pass topology is designed as input matching network (IMN) based on a simplified GaN HEMT model.

2. Equivalent Circuit and Network Topology

The optimal matching topology of the transistor is mainly determined by the reactive constraints. One of the most widely accepted GaN HEMT model is shown in Fig.1 [27–30], which is simplified as possible to guide the circuit design. In the equivalent circuit, Ld and Lg are package lead inductance, LdB and LR_B are bond wires inductance, C11 and C21 is the ceramic package capacitance, Cgs and Cds is the parasitic capacitance. Clearly, the output reactive constraint is LC low-pass type.

For a broadband matching network design, a wider bandwidth usually require higher order of LC-ladder sections as described in [15]. This means the low-pass form of parasitic parameters can be easily absorbed into the design of...
matching network, and extend the design bandwidth simultaneously. [21] and [25] also point out that LC low-pass matching networks are suitable for situations where the load is a low-pass topology. Therefore, low-pass type matching network is totally appropriate for the output term of the transistor based on the equivalent circuit of GaN HEMT.

Nevertheless, the conventional LC low-pass matching networks cannot realize sharp roll-off transition falls out of the design band, which causes the PAE of PAs decreased consequently. As for the elliptic LPF MN proposed in this letter, it is converted from the low-pass filter, and has reserved the similar in band behavior as the former. Moreover, it can offer a sharply roll off out of the design band by adding two attention poles. Hence, the elliptic low-pass type structure shall be one of the optimal choices for the output matching network in this letter. As for the transistor input, the series $C_{gs}$ has been treated as the main factor of reactive resistance [31]. By omitting the package and parasitic elements, the reactive resistance is now a series RLC type. Similarly, for input matching networks, the optimum topology shall be the band-pass type structure, due to the reactive constraints [21].

3. Design Approach for Matching Networks

3.1 The Optimal Source/Load Impedance

This design aims to achieve a realizable bandwidth covering 1.45-2.55 GHz. Both output power and PAE contours are acquired by the source/load pull simulation in ADS software. The contours for the load impedance should be satisfied with output power >41 dBm and PAE >65% across the band, as shown in the smith chart of Fig.3. The impedance inside three different contours represents the optimal impedance of for different frequencies, i.e., 1.5 GHz, 2 GHz and 2.5 GHz, respectively. The optimal source impedance can be acquired in the same way. Meanwhile, the impedance of harmonics should have no real part, in order to further improve the efficiency. The dash area shows the overlapping part of the optimal impedances for the entire frequency band of 1.45 GHz - 2.55 GHz.

3.2 Elliptic low-pass MN with two attenuation poles

In order to further control the second harmonic, the output topology must strike a balance between harmonic suppression and design complexity. An approach to design a modified elliptic LPF matching networks with two attenuation poles is presented below. As analyzed in [23], a real-to-complex Chebyshev low-pass LC-ladder matching network can be achieved and optimized as shown in Fig.4(a). Based on the Chebyshev low-pass matching network, we transform $C_1$ and $C_3$ into two LC series to generate two attenuation poles, as shown in Fig.4(b).

Two Principles should be followed in the transformation process: 1) the resonant frequency of series-resonant branch should lie in the region of second harmonic; 2) the reactive resistance of the branch should remain unchanged after the transformation, which can bring little affect to the fundamental frequency match.

As described in Eq.(1),(2), $f_p$ is the cutoff frequency of the branch, and $f_c$ represents the center frequency in this design, $X_C$ is capacitive reactance and $X_L$ is inductive reactance:

$$f_p = \frac{1}{2\pi\sqrt{L_s C_s}}$$  \hspace{1cm} (1)

$$X_{C_1} = X_{L_1} - X_{C_2} = 2\pi f_c \cdot L_s - \frac{1}{2\pi f_c C_s}$$  \hspace{1cm} (2)

It can be inferred from Eq.(1), (2) that:

$$L_s = \frac{1}{C_1 \cdot \left[\left(2\pi f_p\right)^2 - \left(2\pi f_c\right)^2\right]}$$  \hspace{1cm} (3)
The corresponding design is listed as follows [21]:

\[ Y_2 = \frac{\tan^2 \theta - 1}{2 \tan^2 \theta} \left[ \frac{Y_0 \omega_C C'_c}{g_0} \tan \theta + Y_0 \left( M_{2,3} - \frac{J_{2,3}}{Y_0} \right) \right] \]  

\[ Y_{2,3} = J_{2,3} = \sqrt{\frac{C_2 C_3}{8 g_0}} \]  

Thus, the two attenuation poles with different resonant frequencies can be generated in terms of Eq. (3), (4). The performance contrast of S21 and S11 among Chebyshev low-pass MN, modified Elliptic LPF with one or two attenuation poles is shown below. Clearly, it can control the second harmonic better by adding two attenuation poles in the circuit, without increasing too much design complexity.

Finally, in order to adapt to the high frequency application, all the lumped elements should be replaced by distributed elements. In this design, the microstrip lines with high-impedance or low-impedance were used to replace inductors and capacitors respectively.

3.3 Realization of a Band-pass Filtering IMN

The band-pass type structure is regarded as the optimum topology for the input matching networks of the transistor as described in Section 3.1. To bypass the difficulty of realizing the band-pass filtering networks, we adopted the band-pass structure developed by Matthaei [23–26].

Fig.6 shows this structure for the case of n = 3, where \( Y_2, Y_{23} \) and \( Y_3 \) refer to the admittance of the transmission lines. The corresponding design is listed as follows [21]:

\[ Y_2 = \frac{\tan^2 \theta - 1}{2 \tan^2 \theta} \left[ \frac{Y_0 \omega_C C'_c}{g_0} \tan \theta + Y_0 \left( M_{2,3} - \frac{J_{2,3}}{Y_0} \right) \right] \]  

\[ Y_{2,3} = J_{2,3} = \sqrt{\frac{C_2 C_3}{8 g_0}} \]  

In Fig.7, the S parameter simulation results show perfect band-pass characteristic of the IMN across the bandwidth.

4. Design and Measurement Results

To verify the proposed method, a circuit topology is implemented on a RO5880 substrate (\( E_r=2.2 \)), which the thickness is 31 mils. The biasing condition of the transistor (CGH40010F) is set at \( V_D = 28 \text{ V}, I_{DQ} = 60 \text{ mA} \). The whole circuit topology of the proposed PA is shown in Fig.8. A band-pass filter-based network is designed as the input matching network in the distributed form, which contributes to good gain flatness for the PA. Moreover, the first stub impedance is doubled for the case of practical dimensions. The parallel R-C network and the resistor in series with the gate bias network contribute to the stability for the circuit. The output matching network is made up of a modified elliptic LPF with two attenuation poles. The drain bias circuit is realized by using a compact broadband bias choke 4310LC from Coilcraft. The photograph of the fabricated PA is shown in Fig.9.
measuring error caused by practical components, inaccurate transistor model and passive losses, it is reasonable that the measured result is slightly lower than the simulation.

Fig. 10 shows 40.4–42.4 dBm of Pout and 69.8%–84.4% of DE in the design band, and the maximum peak of DE is 84.4% at 2.1 GHz. Meanwhile, 10.8–14.8 dB of gain is measured as shown in Fig. 11. Some performance indices are listed in Table I with state-of-the-art.

Table I. Broadband PAs comparison with state-of-the-art

| Ref   | BW(GHz)/% | Gain(dB) | Power(W) | DE(%)   |
|-------|-----------|----------|----------|---------|
| [17]  | 1.45-2.45/51 | 10-12.6  | 11-16.6  | 70-81   |
| [20]  | 1.35-2.5/60  | 15.2-17  | 12.5-18  | 68-82   |
| [21]  | 2-3/40     | 11.5-12.5| >10      | 58-72*  |
| [22]  | 1.7-2.7/66  | 12-13    | >10      | 60-70*  |
| This work | 1.45-2.55/55 | 10.8-14.8| 11-17.3  | 70-84   |

*: Only power-added efficiency was provided.

5. Conclusion

In this letter, a novel circuit topology for the broadband high efficiency PA was proposed. Based on the equivalent circuit model, we proposed to use a band-pass matching network as the IMN, and a modified elliptic low-pass filtering matching network with two attenuation poles as the OMN. Based on the procedure introduced above, the proposed broadband PA has been designed, fabricated, and measured. Analysis of the simulation and measurement results demonstrates the high-performance of the PA. The proposed approach is suitable for realizing broadband high efficiency power amplifiers.

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