An ultra-broadband power amplifier by using a simple analysis method

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Abstract This letter presents a simple approach to design ultra-broadband power amplifiers (PAs). The theories of the hybrid modes class-EFJ PAs are applied. The relationship between the operating frequency and load impedance is analyzed for class-EFJ PAs. By appropriately selecting load impedances at different frequencies, a PA can work well in 1.0-4.0 GHz with high efficiency. In addition, the second harmonic impedance is obtained by combining the selected fundamental impedance and load-pull simulation. For validation, an ultra-broadband high efficiency PA is implemented. Experiments show that output power is from 40.1 dBm to 42.6 dBm and drain efficiency is between 60.6% and 72.7% at the saturation level in 1.0-4.0 GHz. The ACLR is smaller than −27.2 dBc in the same frequency band with an average output power of 35.2 dBm.

Keywords: class-EFJ power amplifier, load impedance, high efficiency, ultra-broadband

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

With the development of communication, the operating bandwidth is becoming larger and larger [1, 2, 3, 4, 5]. To design ultra-wideband power amplifiers (PAs) is an interesting research topic. There are many methods proposed to widen the bandwidth of PAs [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25]. Among many types of PAs, distributed PAs have large bandwidth but low efficiency [6, 7, 8, 9]. Continuous modes have been introduced to realize ultra-wideband PAs [10, 11, 12, 13, 14, 15], which has been a widespread study field. It develops into many kinds of continuous modes PAs [16, 17, 18, 19, 20, 21, 22]. However, processes of implementing these complex continuous mode PAs are complicated. In order to reduce the design complexity of the broadband high efficiency PAs, the PA known as the class-EFJ is proposed in [23, 24, 25]. The class-EFJ PA is suitable for broadband and high efficiency purposes by effectively combing high efficiency of class-EF PAs with large bandwidth of class-J PAs at specific conditions. Compared with conventional continuous modes PAs, it is easier to design an ultra-broadband high efficiency PA by applying class EFJ PAs. However, in [23, 24, 25], the bandwidth characteristics of class-EFJ are not detailed analyzed, and the operating bandwidth of class-EFJ is not maximized.

In this paper, the relationship between the operating frequency and load impedance is analyzed for class-EFJ PAs. By selecting proper load impedances of class-EFJ PAs at different frequencies, the maximum working frequency range can be got as from 1.0 GHz to 4.0 GHz. Moreover, the second harmonic impedance is obtained by setting the selected fundamental impedance when performing load-pull simulation. For validation, a broadband high efficiency PA with operating bandwidth of 1.0-4.0 GHz is implemented.

2. Theoretical analysis

In [23, 24, 25], the Class EF PAs and the Class J PAs are integrated when satisfying certain conditions, and such new combined PAs are called hybrid Class-EFJ PAs. As described in [23, 24, 25], the fundamental impedance \( Z_{f0} \) is expressed as:

\[
Z_{f0} = (1 + j) \ast R^* \quad (1)
\]

where \( R^* \) is the load impedance, which is between 15.89 Ω and 46.29 Ω based on CGH40010F GaN HEMT.

For class-J PAs, the relationship between drain efficiency and \( X_{cds}/R_L \) is shown in Fig. 1(a) in ideal conditions [26]. The \( X_{cds} \) refers to the capacitive reactance corresponding to the drain-source capacitance \( C_{ds} \). \( R_L \) is the optimal load impedance, which is determined as:

\[
R_L = \frac{2 \ast V_{dc}}{I_{max}} \quad (2)
\]

where \( V_{dc} \) is the supplied dc voltage, and \( I_{max} \) is the maximum current of the device.

It can be observed from Fig. 1(a) that the drain efficiency remains at an ideal 78.5% when the value of \( X_{cds}/R_L \) is located between 1 and 2.5, where mathematical expression is as follows:

\[
1 < 1 / \omega C_{ds} R_L < 2 \quad (3)
\]

In this paper, for the CGH40010F transistor, the drain-source capacitance \( C_{ds} \) is 1.22 pF, and the \( R_L \) is 37.3 Ω. The calculated frequency range is from 1.4 GHz to 3.5 GHz. The corresponding related bandwidth is 85.7%.

Similarly, if the theory of the hybrid modes class-EFJ is applied, the (3) is rewritten as

\[
1 < 1 / \omega C_{ds} R^* < 2 \quad (4)
\]

The drain-source capacitance \( C_{ds} \) is taken as 1.22 pF. The operating frequency range is plotted in Fig. 1(b). The area between the red line and the blue line represents the available operating frequency range. When \( R^* \) is 46.29 Ω, the low cutoff frequency can be obtained as 1.0 GHz. When \( R^* \) is
The relationship between drain efficiency and $X_{cds}/R_L$. (b) The relationship between frequency range and $R^*$. 15.89 $\Omega$, the high cutoff frequency can be got as 8.2 GHz. Therefore, the maximum frequency range is from 1.0 GHz to 8.2 GHz, where the corresponding relative bandwidth is 156.5%. Considering performance of the CGH40010F transistor in reality, the available frequency band is from 1.0 GHz to 4.0 GHz. Its corresponding relative bandwidth is 120%. It is significant that it is possible to achieve a PA with 120% relative bandwidth by selecting appropriate $R^*$ at different frequencies.

3. Design and experiment

To verify the validity of the design method presented in this paper, an ultra-broadband high efficiency PA is implemented, employing CGH40010F. Rogers 4350B is used as substrate. The drain and gate bias voltages are set to 28 V and -2.7 V, respectively. Based on Fig. 1(b), the optimal fundamental load impedances at different frequencies can be selected, which are plotted in Fig. 2(b). I-Gen plane and package plane represent different planes of the transistor that are shown in Fig. 2(a). The second harmonic also has important influence on the performance of the PAs. Under conditions of the selected fundamental load impedance, the harmonic load-pull should be performed to obtain the optimal second harmonic impedance. The obtained second harmonic impedances at the I-Gen plane are also plotted in Fig. 2(b), where the second harmonic load impedances refer to corresponding typical impedances at the I-Gen plane with over 65% drain efficiency and above 41 dBm output power.

Proper fundamental matching and harmonic control circuits should be well built to satisfy the impedance shown in Fig. 2(b). Fig. 2(a) is the harmonic control circuits with package parameters of the transistor [27]. As displaced in Fig. 2(a), the micro-strip lines TL1, TL2 TL3 and TL4 are employed and optimized to make the impedances of the second harmonic roughly satisfy requirements shown in Fig. 2(b). The output matching network is also implemented to closely fit the optimum fundamental loads shown in Fig. 2(b). Simplified real frequency technique [28] has been used to synthesize a broadband network.

The complete circuit and parameters are shown in Fig. 2(c).
after optimizing in ADS software. The complete circuit is fabricated. Fig. 2(d) is the photo of the fabricated PA. The impedances at the package and I-Gen plane are simulated and plotted in Fig. 3, receptively. Compared Fig. 3(b) with Fig. 2(b), the load impedance of the designed PA is acceptable. The simulated voltage and current waveforms of drain are also plotted in Fig. 4 at two frequencies. It is significant that the overlap between the voltage and current waveforms is small.

Continuous wave signals are used to test the fabricated PA. The measured results are shown in Fig. 5. The saturated power of from 40.1 dBm to 42.6 dBm can be obtained with a gain of from 10.5 dB to 12.7 dB in 1.0-4.0 GHz. Meanwhile, drain efficiency is between 60.6% and 72.7% in the same interesting frequency band. In order to characterize the linearity of the fabricated PA, the PA is measured by employing a 5 MHz W-CDMA signal with peak-to-average ratio of 6.5 dB. The obtained ACLR are displayed in Fig. 5(c). It is observed that ACLR of smaller than $-27.2$ dBc is got in 1.0-4.0 GHz with around 35.2 dBm average output power.

Meanwhile, drain efficiency of from 29% to 32% is achieved in 1.0-4.0 GHz.

Table I lists the performance of several related PAs. It can be observed that the proposed PA has larger bandwidth than other listed works. Specially, the bandwidth of PA designed in this work is larger than one octave compared with the class EF PA in Ref [29], the conventional class EFJ PA in Ref [8] and the class-J in [30], while having similar drain efficiency. Overall, the proposed method can effectively widen the bandwidth of class EFJ PA, while provide a good balance between drain efficiency and bandwidth.

### 4. Conclusion

This paper proposes a simple approach to implement ultra-broadband PAs. By properly selecting load impedance of class-EFJ PAs at different frequencies, the working frequency range between 1.0 GHz and 4.0 GHz can be obtained. Moreover, under selected fundamental load impedance conditions, the second harmonic impedances corresponding to high efficiency are obtained. For validation, an ultra-broadband PA is implemented. Measurements shows that over 40.1 dBm output power and 60.6-72.7% drain efficiency can be obtained in 1.0-4.0 GHz. It indicates that the designed PA has a larger bandwidth, compared to other PAs. Meanwhile, a good balance of efficiency and bandwidth is achieved. This makes it highly desirable for practical applications.
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