Design of broadband high-efficiency power amplifiers based on the harmonic-tuned

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Abstract: A novel methodology for designing broadband high-efficiency power amplifiers (PAs) based on the harmonic-tuned is presented in this letter. All harmonics can be effectively manipulated by the innovative structure to achieve high-efficiency and the dual frequencies point harmonic matching method is also applied to the harmonic control network, which has a positive effect on the expansion bandwidth. To verify the validity of the proposed methodology, a gallium nitride PA is designed, implemented, and measured. Measured results manifest a wide bandwidth from 1.1 to 2.5 GHz, with drain efficiency (DE) of 67–86%, saturated output power greater than 39.5 dBm, and large signal gain larger than 9.5 dB. The in-band second and third harmonic suppression levels are maintained at $-13$ to $-36$ dBc and $-23$ to $-44$ dBc, respectively. Measurement results confirm the theoretical findings reported in this paper.

Keywords: high-efficiency, broadband, harmonic-tuned, dual frequencies point harmonic matching, power amplifiers

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

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1 Introduction

With the evolution of the modern wireless communication technology, communication systems is required to have higher efficiency and wider operation bandwidth [1, 2]. The PA, as one of the most crucial components in the system, is also requested to have the ability of working in multiband. Meanwhile, since the PA is an important energy consumer, the efficiency of the whole system is largely determined by the efficiency of the PA [3, 4]. Recently, the harmonic-tuned PAs have caused public concern because it is one of key technologies to improve the efficiency. However, there are two limitations in the traditional harmonic-tuned PAs, one is the limited orders of harmonics-tuned, which leads to the blocked efficiency improvement, and the other is the narrowband characteristics of the harmonic control network severely restrict the bandwidth, such as traditional Class-F [5] and inverse Class-F [6].

To overcome the above mentioned narrowband problem, a series of continuous modes are proposed, like continuous Class-F [7], continuous Class-B/J [8], and continuous inverse Class-F [9], which have a positive effect on the expansion bandwidth. Nevertheless, the continuous modes are still unable to control higher order harmonics, so the efficiency cannot be further improved.

In order to achieve both efficiency improvement and bandwidth expansion, a methodical design approach is presented to design a broadband high-efficiency PA which employs a novel topology to manipulate all harmonics and dual frequencies point harmonic matching method is implemented to the harmonic control network. For the purpose of validation, a high-efficiency and broadband PA is designed and fabricated over the frequency band of 1.1–2.5 GHz with a relative bandwidth of 78%. The designed PA realizes drain efficiency greater than 67% and the 86% can be attained in the highest point. The experimental results reveal that...
the performance of PA is superior to traditional harmonic-tuned and continuous modes.

2 Design of broadband high-efficiency PA

2.1 The theory of harmonic-tuned

According to the theory of harmonic-tuned [5], high-efficiency PA operation is achieved by saturating the device and manipulating the generated harmonics in such a manner as to produce nonoverlapping drain waveforms. Harmonics effect on drain voltage waveform is drawn in Fig. 1. It is clear that the effect of the adding harmonics is basically to shape voltage waveform changed from sinusoidal to square wave. It can be seen from the Fig. 1 that the higher order harmonics are manipulated, and there are better effects of voltage waveform shaping.

For instance, as a typical harmonic-tuned PA, Class-F operation demands open-circuit terminations at odd harmonics, with short-circuit terminations at the even harmonics [5]. These waveforms are described by the following equations:

\[ i_D(t) = I_0 + \sum_{\delta=1}^{2k} I_\delta \cdot \cos(\delta \omega t + \alpha_\delta) \quad k = 1, 2, 3 \ldots \]  \hspace{1cm} (1)

\[ V_{DS}(t) = V_{DD} - \sum_{m=1}^{2k+1} V_m \cdot \cos(m \omega t + \beta_m) \quad k = 1, 2, 3 \ldots \] \hspace{1cm} (2)

where \( \alpha_\delta \) and \( \beta_m \) are the phases of the output current and voltage at the \( \delta^{th} \) and \( m^{th} \) order, respectively.

Base on the above definition, the DC and drain dissipation of transistors can be calculated as follows:

\[ P_{DC} = V_{DD} \cdot I_0 \] \hspace{1cm} (3)

\[ P_{diss} = \frac{1}{T} \int_0^T V_{DS}(t) \cdot i_D(t) dt. \] \hspace{1cm} (4)
The power of each harmonic can be determined as follow:

$$P_{out,nf} = \frac{1}{2} \cdot V_n I_n \cdot \cos(\phi_n).$$

(5)

where \(n\) is the order of the harmonics. Therefore, the drain efficiency can be calculated as follows:

$$\eta_{\text{drain}} = \frac{P_{out,f_1}}{P_{\text{DC}}} = \frac{P_{out,f_1}}{P_{\text{diss}} + P_{out,f_1} + \sum_{n=2}^{\infty} P_{out,nf_1}}.$$  

(6)

In Eq. (6), \(P_{\text{diss}}\) is the dissipation caused by the overlap of drain current and voltage waveforms. So, from the point of view the theory of harmonic-tuned, as long as all harmonics can be effectively control, each harmonic will not consume energy, and the drain efficiency of 100% can be achieved.

### 2.2 Design of harmonic control circuit

Based on the theory of harmonic-tuned and conventional thought of harmonic control, considering the hardness of matching circuit design and the limited area of the circuit board, it is very difficult to manipulate all harmonics. To solve the above issue, a generic fabric is proposed by utilizing the periodic variation principle of harmonic impedance.

The presented circuit topology is shown in Fig. 2 and all the parameters are labeled. First, the design parameters TL1, TL2 and TL3 are chosen as \(\lambda/4\) for the fundamental frequency. It can be seen from the even harmonics regulation in the figure that originating from the principle of quarter-wave impedance transformation, combined with the quarter wavelength short-circuit stub TL1 operating at all even harmonics, the input impedance of the \(Z_{\text{in1}}\) can be determined as follow:

$$Z_{\text{in1}} = Z_{2n} = jZ_1 \tan \left( \frac{\pi f_{2n}}{2 f_1} \right). \quad n = 1, 2, 3 \ldots$$

(7)

where the characteristic impedance of stubs \((Z_1)\) is the free design parameters, \(f_{2n}\) is the \((2n)\)th harmonic, \(Z_{2n}\) is impedances of even harmonics, and \(f_1\) is the fundamental frequency.

In the odd harmonics regulation section, the quarter wavelength open-circuit stub TL2 is employed together with a transmission line TL3 operating at all odd
harmonics. Thus, the input impedances of the $Z_A$ and $Z_{in2}$ can be determined separately, as follows:

$$Z_A = -jZ_2 \tan \left[ \frac{\pi f_{2n+1}}{2 f_1} \right], \quad n = 1, 2, 3 \ldots \quad (8)$$

$$Z_{in2} = Z_{2n+1} = jZ_3 \tan \left[ \frac{\pi f_{2n+1}}{2 f_1} \right], \quad n = 1, 2, 3 \ldots \quad (9)$$

Similarly, the characteristic impedance ($Z_2$ and $Z_3$) of transmission line are the free design parameters, $f_{2n+1}$ is the $(2n+1)$th harmonic, $Z_{2n+1}$ is impedances of odd harmonics, and $f_1$ is the fundamental frequency.

Based on Eq. (7) (9), it can be concluded that the impedances of even harmonics is matched to zero, odd harmonics to infinite. Therefore, the impedances of all harmonics can be calculated as follows:

$$\begin{cases} 
Z_{2n} = 0 & n = 1, 2, 3 \ldots \\
Z_{2n+1} = \infty & n = 1, 2, 3 \ldots 
\end{cases} \quad (10)$$

### 2.3 Broadband high-efficiency matching network design

The operation bandwidth is severely limited by employing a high-Q harmonic control network in traditional harmonic-tuned PAs [5]. Hence, the dual frequencies point harmonic matching method is proposed to make up for the imperfection, in this letter. To expand the bandwidth, two frequency points 1.5 GHz and 2.1 GHz are selected to design output matching the harmonic control circuit, respectively. Meanwhile, using a approach of stepped-impedance matching for fundamental frequency, the input matching network is also put forward. The broadband high-efficiency PA including input matching and output matching realized by using transmission lines is depicted in Fig. 3 and all parameters are labeled.

To validate the feasibility of the proposed design approach, simulated drain voltage and current waveforms at two frequencies of 1.5 GHz and 2.1 GHz are drawn in Fig. 4. These approximately interlaced waveforms manifest the presented harmonic-tuned is achieved at these frequencies. Meanwhile, in order to further demonstrate the advantages, the simulated impedance of the second harmonic, third
harmonic, fourth harmonic, and the fifth harmonic on the Smith chart are illustrated in Fig. 5. It indicates that the impedances of the even harmonics and the odd harmonics is commendably maintained in the low impedance and high impedance region over the entire bandwidth separately.

![Fig. 4. The results of the simulated drain voltage and current waveform. (a) at 1.5 GHz and (b) at 2.1 GHz.](image)

![Fig. 5. The results of the simulated second to fifth harmonics impedances.](image)

### 3 PA fabrication and measurement results

A broadband high-efficiency PA is implemented on a Rogers 4350B substrate with and thickness of 0.762 mm, employing Cree’s CGH40010F HEMT to validate the preceding theory. A photograph of the fabricated with a dimension of 89 mm × 61.5 mm is shown in Fig. 6.

To measure the large-signal of PA, a measurement platform consisting of a signal generator (Agilent E8257C) and a power meter (Agilent E4416A) is used and the test signal is selected as a single-tone CW signal from 1.1 to 2.5 GHz with 0.1 GHz step. The gate bias is set as −2.7 V and the drain voltage is set as 28 V. Fig. 7 shows the measured and simulated large-signal test results over the whole bandwidth using an input power of 30 dBm. The measured saturated output power, drain efficiency and gain are between 39.5–42 dBm, 67–86% and 9.5–12 dB, respectively. As anticipated, the drain efficiency curvilineal has two local maxima
at 1.5, and 2.1 GHz, which corresponds to the two frequencies selected to the harmonic matching.

Fig. 8 illustrates measured second to fifth relative harmonics level to fundamental frequency output power. When working below 1.3 GHz, the second harmonic is considerable because it falls in the fundamental bandwidth. The harmonic levels are maintained at $-20$ to $-36$ dBc as the favorable harmonic impedances are provided by harmonic-tuned network at 1.3 to 2.5 GHz. The third to fifth harmonic suppression levels across the band are maintained at $-23$ to $-44$ dBc, $-28$ to $-46$ dBc, and $-28$ to $-46$ dBc separately. Measured DE, power added efficiency (PAE), and gain against the corresponding output powers at different operation frequencies are illustrated in Fig. 9. It can be observed that when the output power are 40.5 dBm and 42 dBm, the gain is compressed to nearly 3 dB and the corresponding input is 30 dBm. At the moment, the maximum drain efficiency of 86%, 78.2% and PAE of 81%, 72% are obtained at 2.1 GHz and 1.5 GHz, respectively. A comparison with some recently reported broadband high-efficiency PAs is outlined in Table I and the proposed PA demonstrates outstanding efficiency performance while its broadband characteristic is comparable with other state-of-the-art broadband PAs.
4 Conclusion

In this paper, a systematic method is introduced to design output matching networks for broadband high-efficiency PAs. Following on from a previous paper, further novel theory of harmonic-tuned has been presented and combined with the dual frequencies point harmonic matching method for efficiency enhancement in a broad bandwidth. The proposed procedure has been demonstrated by implementing...
a PA, based on GaN HEMT device. Measurements of the fabricated amplifier reveal the PA delivers 8.9–15.8 W saturated output power with a DE of 67–86%. The second and the third harmonic suppression levels are maintained at −13 to −36 dBc and −23 to −44 dBc, respectively. The simulated and measured results show good performances on all the indicators.

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