Design of multi-octave continuous power amplifier based on broadband matching technique

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Abstract This paper presents a multi-octave broadband continuous power amplifier based on the simplified real frequency method. By analyzing the load-pull impedance trajectory along with frequency increase at both ends of the transistor’s input and output, the input impedance value of the matching circuit can be more coincident with the pull data in the wide band range, which meets the requirement of expanding the bandwidth of the power amplifier. Meanwhile, combining with simplified real frequency method, it can greatly simplify the process of designing broadband matching network. In order to verify the validity of the theory, the power amplifier is designed and fabricated. The measured results show that the maximum output power reached 42.5dBm and the drain efficiency is from 63% to 71% in the 1-3.2 GHz frequency band.

Keywords: continuous, multi-octave, power amplifier, simplified real frequency method, drain efficiency

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

1. Introduction

With the rapid development of communication technology, many countries have officially entered the era of 5G [1, 2, 3, 4]. In the 5G communication, one of the most important technical features is the ability to connect potentially tens of billions of things with high bandwidth and low latency [5]. Higher requirements are placed on the performance of the designed radio frequency (RF) power amplifiers (PAs). In particular, it is required to meet the requirements of wide bandwidth [6].

At present, the expansion of amplifier bandwidth by designers adopt the idea of continuous class [7, 8, 9, 10]. With the increase of harmonic control factor, the area of optimal impedance solution is expanded. Unfortunately, the design process of continuous class is arduous because the load network matched at several frequency points. Several broadband PAs are designed and realized based on the in-band continuous class mode-transferring operation [11] and multi-stage transmission-line-based low-pass matching network [12, 13]. The series of continuous modes with the fundamental impedance real part variation give more design freedom to realize broadband high-efficiency PA [14]. Using filter structure as the matching circuit, the broadband design can be realized by filtering the high harmonics. However, there are some difficulties in the design of the in-band attenuation and transition band of the filter structure, and it is difficult to precisely realize the design of the specified frequency band. Due to the difficulty of impedance solution in designing continuous amplifiers, many scholars used network synthesis method and algorithm to optimize them. A two-port network is established by using the scattering parameters, and a lossless matching network is optimized [15, 16, 17, 18, 19]. In addition, the designer adopts the hybrid class harmonic control network to make the amplifier work in different class J/F/F⁻¹ at different frequency points, which expands the bandwidth beyond one octave. Ultra-wide band PAs employ both series of continuous and inverse continuous modes are examined [20, 21, 22], the solution spaces of fundamental impedance are expanded. In [23], a phase shift parameter is introduced in the voltage waveform formula of the hybrid continuous mode between class J and continuous class F. Although the idea of mixed class can extend the bandwidth, the matching circuit structure of controlling multiple frequency points is relatively complex, which requires precise control harmonics at each frequency point. Lots of carefully debug is required to achieve good performance.

In order to reduce the difficulty of existing work and further expand the bandwidth, this paper uses the GaN high electron mobility transistor (HEMT). By analyzing the rule of the optimal impedance data of the transistor’s load-pull and source-pull with the frequency variation, the input impedance of the designed matching circuit is coincident with the optimal impedance value at more frequency points. A broadband amplifier is designed, and then the design process is simplified by using simplified real frequency method.

2. Principles of theoretical analysis

2.1 Extension of continuous modes

Compared with the traditional class-F mode, continuous class-F mode greatly expands the design space. Since the second harmonic impedance is pure reactance, the design of amplifiers with bandwidth exceeding one octave is limited. An extended continuous mode amplifier is proposed to maintain higher average efficiency in a wide band [14]. Ideal inverse class F power amplifier transistor current to the voltage and current waveform are a half sine wave and a square wave, respectively. Similar to continuous class-F amplifier, the continuous inverse class-F work mode was proposed by Carrubba [24], which adds two variables to expand into a
The extended continuous inverse class-F fundamental wave, second harmonic and third harmonic admittances are written as follows:

\[ i(\theta) = (i_{DC} - i_1 \cos \theta + i_3 \cos 3\theta) \cdot (1 - \gamma \sin \theta) \]  
\[ i(\theta) = (1 - k_1 \cos \theta + k_3 \cos 3\theta) \cdot (1 + \alpha \cos \theta) \cdot (1 - \gamma \sin \theta) \]

where \(-1 \leq \gamma \leq 1\), \(i_1 = 0.37\), \(i_2 = 0.43\), and \(i_3 = 0.06\).

The extended continuous inverse class-F fundamental wave, second harmonic and third harmonic admittances are written as follows:

\[ Y_{1,CF-1} = \sqrt{2}(k_1 - \alpha) + j\gamma \left[ 1 - \frac{\alpha}{4}(k_1 + k_3) \right] \]  
\[ Y_{2,CF-1} = \alpha(k_1 - k_3) + j\gamma(\alpha - k_1 - k_3) \]  
\[ Y_{3,CF-1} = \infty \]

### 2.2 Simplified real frequency method (SRFM)

The performance of the matching circuit is usually measured by transducer power gain (TPG). TPG is defined as the ratio of load input power to source output power, which is the main optimization parameter of SRFM.

The lossless matching network between the transistor output end and the terminal load is regarded as a balanced network \(E\) in a wide frequency band. \(E_{12}(s)\) is the normalized reflection coefficient of the port. Both \(h(s)\) and \(g(s)\) are Hurwitz polynomials of \(n\) terms. Through the rule of lossless network, the relation of \(h(s)\) and \(g(s)\) meets the following condition:

\[ g(s) \cdot g(-s) = h(s) \cdot h(-s) + f(s) \cdot f(-s) \]  
\[ f(s) = s^k \]

where \(f(s)\) can be constructed by specifying the number of transmission zeros matching on the network, \(k\) is the number of transmission zeros. The scattering parameters of the lossless reciprocity network can be obtained by the molecular polynomial \(h(s)\), which is an important idea to simplified the real frequency method.

In Fig. 1, it is assumed that the output impedance of the transistor is \(Z_{opt}(s)\), which is matched to the terminal resistance load \(R_L\) through the network \(E\) in a wide frequency band. \(E_{ij}(i,j = 1,2)\) is the normalized scattering parameter of the transistor. \(L_{ij}(i,j = 1,2)\) is the normalized scattering parameter of the transistor. The transmission power gain is expressed as:

\[ TPG = \frac{|E_{21}|^2 \cdot |L_{21}|^2}{|1 - E_{22}L_{11}|^2} \]

### 3. Multi-octave amplifier design process

#### 3.1 Design of output-matching network

The key to the design of broadband power amplifier is the realization method of broadband matching network. According to the theoretical analysis and brief discussion of the real frequency method in the previous section, the impedance data of each frequency point in the frequency band should be provided when the real frequency synthesis method is used in the design of power amplifier.

The load-pull impedance is related to the transistor working point, input power and working frequency. In this design, the transistor gate bias is set to \(-2.8\) V, the drain voltage is 28 V, the input power is 28 dBm, and the sweep frequency is from 1.0 GHz to 3.2 GHz, where the frequency interval is 0.2 GHz. Figure 2 shows the load-pull impedance trajectory with frequency, where the black triangle represents the load impedance at the highest power added efficiency (PAE), and the hollow triangle shows the combined value of the load impedance corresponding to the highest PAE and the maximum output power at the same frequency point.

From the analysis of the impedance-frequency variation trend, when the working frequency increases, the optimal load impedance moves from the inductance area to the capacitance area of the Smith chart while the reactance moves from the outside of the chart to the outside, indicating that the reactance decreases with the increase of frequency. Overall, the output load impedance of transistor’s parasitic rotates by counterclockwise with the increase of frequency. Through the previous analysis, the physical can realize the impedance matching circuit with the increase of the frequency and the clockwise direction, which is a filtering structure [26]. At this point, the load impedance \(Z_L\) matched to the optimal impedance \(Z_{opt}\), however, the direction of the two impedance trajectories is opposite. The two impedance trajectories can only achieve good matching at the intersection points or a short band.

To illustrate the principle of broadband matching, the two intersecting impedance characteristic curves \(Z_{opt}\) and \(Z_L\) in Fig. 2 will be analyzed. \(Z_{opt}\) represents the optimal impedance of the transistor, and \(Z_L\) represents the load impedance seen from the output end of the transistor. As the frequency increases, the former rotates by counterclockwise, and the latter rotates by clockwise. It is not hard to see that two curves intersect points corresponding to the two indicators at local maximum, thus it expands the bandwidth. But between the two points of intersection, the output power will be reduced due to impedance mismatch. The above re-
Table 1: Load and source optimization of impedance

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Zopt (load/θ)</th>
<th>Frequency (GHz)</th>
<th>Zopt (source/θ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.5+j*19.6</td>
<td>1</td>
<td>16.1+j*5.4</td>
</tr>
<tr>
<td>1.5</td>
<td>17.2+j*16.4</td>
<td>1.5</td>
<td>12.2+j*5.4</td>
</tr>
<tr>
<td>2</td>
<td>19.6+j*16.8</td>
<td>2</td>
<td>7.4+j*3.8</td>
</tr>
<tr>
<td>2.5</td>
<td>16.5+j*5.97</td>
<td>2.5</td>
<td>8.4+j*0.14</td>
</tr>
<tr>
<td>3</td>
<td>13.8+j*2.6</td>
<td>3</td>
<td>8.8+j*7</td>
</tr>
</tbody>
</table>

The load and source optimization of impedance curve can be realized by means of series and parallel resonant circuit or filter.

According to the results of the load-pull in the Table I, using the SRFM algorithm, the optimization goal of TPG is set to 0.9 and frequency range is from 0.5 GHz to 4 GHz. Finally, using integrated third-order LC circuit prototype, the LC output matching circuit and simulation results of S-parameters are shown in Fig. 3 and Fig. 4. Fig. 3 is a lumped parameter third-order LC low-pass structure.

3.2 Design of input-matching network

The design procedure of the input matching network is similar to that of the output matching network. The optimal source impedance distributed on Smith chart is shown in Fig. 5. As you can see from it, the optimal source impedance rotates by counterclockwise with the increase of frequency values. The optimal impedance move to the capacitance area from the inductance area. When it works at more than 1.4 GHz frequency, source impedance moves to the capacitance area, as conjugate transistor input impedance is inductive. Through the analysis shows that the actual impedance matching circuit is clockwise with the increase of frequency, it is conducive to the input matching circuit design of broadband.

In the design of wideband harmonic control amplifier, the result of source-pull should not be neglected in order to obtain high output power and drain efficiency.

Fig. 5 Simulation of source-pull and matching analysis

Similar to the output-matching network design, source-pull impedance data of each frequency point will be calculated using the simplified real frequency optimization program. The frequency covers from 0.5 GHz to 3.3 GHz. Finally, the lumped parameter of the input matching circuit and simulation results of S-parameter are demonstrated in Fig. 6 and Fig. 7.

Fig. 6 Optimized input matching network

The multi-section ladder resonant LC network is converted into the form of microstrip line by Richard transform and Kiruoda’s rule [27] and the amplifier is tested and simulated at radio frequency. Finally, the multi-octave output and input matching network are designed and optimized. After the simulation and optimization, the schematic of the multi-octave PA is illustrated in Fig. 8.
4. Implementation and measurement

According to the above method, the power amplifier circuit is designed using CGH40010F GaN HEMT based on Rogers 4350B (relative dielectric constant of 3.66, substrate thickness of 30mil). The gate voltage is set to 2.8 V, the drain bias voltage is set to 28 V, which makes the PA working at class-AB. And the final fabricated power amplifier is shown in Fig. 9.

![Photograph of the fabricated PA](image)

Fig. 9 Photograph of the fabricated PA

![Complete circuit schematic of the proposed PA](image)

Fig. 8 Complete circuit schematic of the proposed PA

Fig. 10 shows the measured results of small signal test from 0.5 GHz to 7 GHz. Good small signal gain ($S_{21}$) is obtained in the low frequency range. Fig. 11 presents the simulation and test results of the designed power amplifier. It can be seen that in the 1-3.2 GHz band, when the input power is 30 dBm, the measured values of the drain efficiency are between 63% and 71%. The simulation value at 1 GHz is 63%, which is lower than that of the measured value. Because the distribution parameters of the circuit can’t make up for the adverse factors. The remaining efficiency is between 65%-70%, and the flatness is good. The measured output power is between 38.8-41.7 dBm, the simulation results are all exceed 40 dBm. The value of the highest measured gain is 11.6 dB, the gain is 9.4 dB at 3.1 GHz, the gains at other frequency points are all greater than 10 dB. Fig. 12 shows the relationship between the measured drain efficiency, gain and output power. When the output power reaches 42 dBm, the drain efficiency does not increase any more.

![Simulated and measured output power, drain efficiency and gain.](image)

Fig. 11 Simulated and measured output power, drain efficiency and gain.

The amplifier gain begins to decline at the output of 40 dBm and then decreases rapidly as the output power increases. The measurement results of efficiency, output power and gain are in good agreement with the simulation results.

![Measured drain efficiency and gain vs output power for different frequencies.](image)

Fig. 12 Measured drain efficiency and gain vs output power for different frequencies.
of 1–3.2 GHz. Compared to other related PAs, drain efficiency is from 63% to 71% in the frequency range. The measured results show that the proposed PA has a larger bandwidth than that of other related PAs. It can be seen from the Table II that the proposed PA takes various aspects of the indicators into account such as bandwidth, power and efficiency so that better practical applications can be achieved.

5. Conclusion

This paper presents a multi-octave broadband continuous power amplifier based on the SRFM. By analyzing the frequency variation rule of the load-pull data at both ends of the transistor’s input and output, the input impedance values of the matching circuit are more coincident with the source-pull data in the wide band range. Meanwhile, combining with SRFM, it can greatly simplify the process of designing broadband matching network. The measured results show that the maximum output power up to 42.5 dBm and the drain efficiency is from 63% to 71% in the frequency range of 1–3.2 GHz. Compared to other related PAs, which shows that the proposed PA has good performance both efficiency and bandwidth. It is very suitable for practical application.

Table II [28, 29, 30] lists the performance comparison of some related PAs. It can be clearly observed that the proposed PA has a larger bandwidth than that of other related PAs. It can be seen from the Table II that the proposed PA has a larger bandwidth than that of other related PAs. It can be clearly observed that the proposed PA has a larger bandwidth than that of other related PAs. It can be seen from the Table II that the proposed PA has a larger bandwidth than that of other related PAs. It can be clearly observed that the proposed PA has a larger bandwidth than that of other related PAs.

Table I

<table>
<thead>
<tr>
<th>Refs</th>
<th>$f_{	ext{eq}}$ (GHz)</th>
<th>$\eta$ (%)</th>
<th>$P_{\text{out}}$ (dBm)</th>
<th>Gain (dB)</th>
<th>BW (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[28]</td>
<td>2.2–2.8</td>
<td>65.9–79.7</td>
<td>39.6–41.3</td>
<td>9–12.2</td>
<td>24</td>
</tr>
<tr>
<td>[29]</td>
<td>1.6–2.4</td>
<td>52–73</td>
<td>38.7–39.7</td>
<td>11.5–13</td>
<td>40</td>
</tr>
<tr>
<td>[30]</td>
<td>1.3–2.4</td>
<td>70–86</td>
<td>37–40</td>
<td>9.1–12</td>
<td>64</td>
</tr>
<tr>
<td>[11]</td>
<td>1.3–3.3</td>
<td>70–87</td>
<td>40–40.3</td>
<td>9.8–11.5</td>
<td>87</td>
</tr>
<tr>
<td>[23]</td>
<td>1.2–3.6</td>
<td>60–72</td>
<td>40–42.2</td>
<td>10.5–12</td>
<td>100</td>
</tr>
<tr>
<td>This work</td>
<td>1.3–2.2</td>
<td>63–71</td>
<td>38.8–41.7</td>
<td>9.4–11.6</td>
<td>104</td>
</tr>
</tbody>
</table>

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