A broadband high efficient Class-J power amplifier with compact matching network

Guohua Liu, Zhiwei Zhang\textsuperscript{b)}, Zhiqun Cheng\textsuperscript{a)}, Sudong Li, and Ming Zhang

\textit{Key Lab. of RF Circuit and System, Education Ministry, Hangzhou Dianzi University, Hangzhou 310018, China}
\textsuperscript{a)} zhiqun@hdu.edu.cn
\textsuperscript{b)} 13588084606@163.com

Abstract: A broadband high efficiency Class-J power amplifier (JPA) with new output impedance calculation method is proposed. A compact low-pass output matching network and an opened-sector microstrip line instead of a parallel capacitor are employed to provide impedance space for broadband design. To enhance the bandwidth, a multi-stage Chebyshev low pass matching network is used with input matching network. For demonstration, a broadband high efficient JPA based on proposed structure is designed and fabricated. Measurement results show that the drain efficiency between 55\%–67\%, output power from 40 to 42.6 dBm with more than 10 dB gain over a bandwidth of 1.0–3.0 GHz, accounting for 100\% fractional bandwidth. When employed by a 5 MHz WCDMA signal with 8-dB peak-to-average power ratio (PAPR), the adjacent channel power ratio (ACPR) between $-24.1$ and $-32.4$ dBc without digital predistortion (DPD).

Keywords: Class-J, high efficiency, broadband, radial microstrip line, compact matching network

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

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1 Introduction

High efficiency and wide bandwidth clubbed together are extremely desirable characteristics of modern power amplifiers (PAs), due to modern communication systems pursuing higher data rates and more flexible frequency [1]. As consequence, the research of power amplifier has increasingly concerned with bandwidth and efficiency. It is reported that the Power Added Efficiency (PAE) has exceeded 70% for Class F/F⁻¹ and Class E operation, which rely on a very specific impedance environment, limiting their bandwidth of operation and making linearity worse [2].

Class-J PA mode is proposed by S. C. Cripps which not only provides the same efficiency and output power as Class-B PA but also obtains broader bandwidth [3, 4]. Many improvements to the Class-J operation mode have been reported in recent works [5, 6, 7]. Implementations of Class-J PA with packaged transistors have been proven to achieve excellent performance in efficiency and bandwidth [5]. An output match design method for high efficiency and broadband class-J PA has been verified by the design, simulation and measurement [6]. In [7] the broadband B/J continuous mode of the PA is implemented which has 63% to 72% drain efficiency in the 1.3–2.4 GHz.

In this paper, a novel output match method is proposed for the design of broadband high efficiency Class-J PA. Compared with the traditional Class-J PA, the proposed output match method not only achieves a compact matching structure but also balances efficiency and power in the broadband range. In this work, the theoretical analysis is presented and a 1.0–3.0 GHz wideband high efficiency PA is designed to validate the proposed output match method.
2 Analysis and design of Class-J power amplifier

The Class-J power amplifier allows a large number of second-harmonic reactance components. Meanwhile, the fundamental impedance must contain the reactance component so that the voltage waveform is greater than zero, thus maintaining good linearity. For Class-J amplifier, the fundamental and second-harmonic output impedances are given by \[ Z(f_0) = R_L (1 + j) \] (1)
\[ Z(2f_0) = R_L \left( 0 - j \cdot \frac{3\pi}{8} \right) \] (2)

Where \( Z(f_0) \) and \( Z(2f_0) \) represent the fundamental and second-harmonic output impedance, respectively. \( R_L \) is the load impedance.

The sector microstrip stub is shown in Fig. 1a, which input impedance can be given as follows

\[ X_{\text{secin}} = \frac{h}{2\pi r_1} Z_0(r_1) \frac{360 \cos(\theta_1 - \phi_2)}{\alpha \sin(\theta_1 - \phi_2)} \] (3)
\[ \tan \theta_1 = \frac{N_0(kr_1)}{J_0(kr_1)} \] (4)
\[ \tan \phi_i = -\frac{J_1(kr_1)}{N_1(kr_i)}, \quad i = 1, 2 \] (5)
\[ Z_0(r_1) = \frac{120\pi}{\sqrt{\varepsilon_r}} \left[ J_0^2(kr_1) + N_0^2(kr_1) \right]^{1/2} \rho \left[ J_1^2(kr_1) + N_1^2(kr_1) \right]^{-1/2} \] (6)
\[ k = 2\pi \sqrt{\varepsilon_r / \lambda_0} \] (7)

\( J_i(x) \) and \( N_i(x) \) are Bessel functions of the first and second type, \( \alpha, r_1 \) and \( r_2 \) represent the angle, the inner and outer radii of the sectorial microstrip stub, respectively. \( \lambda_0 \) is the wavelength of free space. \( \varepsilon_r \) is the equivalent dielectric constant, and \( h \) is the thickness of the dielectric substrate.

![Fig. 1. Sectoral microstrip stub and two-port network for: (a) Sectoral microstrip stub (b) the compact output two-port network](image)

According to the mutual conversion of the two-port network parameters, the transfer matrix \([A]\) can be expressed as

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} =
\begin{bmatrix}
1 + \frac{Z_1}{Z_L \parallel Z_{\text{sec}}} & \frac{Z_1}{Z_L \parallel Z_{\text{sec}}} \\
\frac{Z_L}{Z_L \parallel Z_{\text{sec}}} & 1
\end{bmatrix}
\begin{bmatrix}
\frac{Z_1 + (Z_L \parallel Z_{\text{sec}})}{Z_{\text{out}}}
\end{bmatrix}
\] (8)
\[ Z_{\text{out}} = Z_1 + Z_L \parallel Z_{\text{sec}} \] (9)
Z1, ZL and Zsec represent impedance of TL1, load and sector microstrip stub, respectively, as shown in Fig. 1b.

In order to achieve the performance of class J amplifiers, the output impedance should meet the following relationship

\[ Z(nf_0) = Z_{\text{out}} = Z_1 + Z_L \parallel Z_{\text{sec}}, \quad n = 1, 2 \] (10)

Substituting equation (3) into (9), there can be obtained

\[ Z_{\text{out}} = \frac{Z_L + Z_1 + (2 \pi n f X_{\text{sec}} Z_L)^2 Z_1 - j \pi n f X_{\text{sec}} (Z_L)^2}{(2 \pi n f X_{\text{sec}} Z_L)^2 + 1}, \quad n = 1, 2 \] (11)

Therefore, using (1) (2) and (11), the required set of optimum parameters of OMN for Class-J can be derived from the following equations:

\[
\begin{align*}
Z_1 + Z_L + 2 \pi n f X_{\text{sec}} (Z_L)^2 & - (2 \pi n f X_{\text{sec}} Z_1 + 1) = 0 \\
X_{\text{sec}} (Z_L)^2 & = 3/32 \\
Z_L + 16 \pi^2 (Z_L)^2 & \times Z_1 + Z_L = 0
\end{align*}
\] (12)

The bandwidth of an opened-sector microstrip line is wider than that of a λ/4 microstrip line. Applying the above theory, a novel compact OMN designed is shown in Fig. 2. In order to broaden the bandwidth of the Class-J amplifier, the parallel grounded capacitor in the matching network is replaced by an opened-sector microstrip line. It is determined that the required output fundamental impedance between 1.0–3.0 GHz by load-pull simulation with results are shown in Fig. 2. The inside regions of the contours represent above 41 dBm of output power and over 60% efficiency. The overlap area is the space designed for the output impedance. The purple trace is the impedance trajectory of the output load network using the compact OMN. It is obvious that the impedance of the output load network lies inside the fundamental impedance contours. Thus, the output design targets are achieved in the bandwidth.

A broadband input matching network based on Chebyshev filter is presented to further enhance bandwidth of amplifier. And a 7:1 Chebyshev impedance transformer is suggested to realize the real-to-real matching from 50 Ω. Fig. 3 shows proposed broadband input matching network based on Chebyshev filter, and the matching traces on the Smith chart.
3 Fabrication and measurement results

A novel Class-J PA based on proposed strategy is designed using a 10-W GaN HEMT CGH40010F device on Rogers RO4350B substrate. The power amplifier is biased at $V_{GS} = -2.7\,V$ and $V_{DS} = 28\,V$. The final designed complete schematic of the proposed Class-J PA and the photograph of the fabricated amplifier circuit are shown in Fig. 4. Drain voltage and current waveforms are shown in Fig. 5 at different frequencies, which validate the operation conditions of the proposed PA. These waveforms suggest that the proposed operation mode is well at these frequencies.

The PA is driven up to its 2-dB compression point for all measurements. The simulated and measured drain efficiency, output power, and gain for every fre-
frequency point from 1.0 to 3.0 GHz are plotted in Fig. 6. Drain efficiency is more than 55%, output power is 40 to 42.6 dBm and gain over 10 dB in the design frequency band. The adjacent channel power ratio (ACPR) under 8-dB peak-to-average power ratio (PAPR) 5-MHz WCDMA signal is shown in Fig. 7. The proposed PA has ACPRs between $-24.1$ and $-32.4$ dBc from 1.0 to 3.0 GHz without digital predistortion.

![Fig. 5](image1.png)

**Fig. 5.** Drain voltage and current waveforms at different frequency

![Fig. 6](image2.png)

**Fig. 6.** Measured and simulated drain efficiency, output power and gain versus frequency

![Fig. 7](image3.png)

**Fig. 7.** Measured ACPR characteristic of the proposed PA
Table I lists the comparison of some published broadband PA and this work.

| Reference | Frequency (GHz) | Bandwidth (%) | DE (%) | Pout (dBm) |
|-----------|----------------|---------------|--------|------------|
| [6]       | 1.9–4.3        | 77            | 53–72  | 40–41.7    |
| [8]       | 0.5–1.8        | 113           | 50–69  | 39–40      |
| [9]       | 1–2.9          | 97            | ≥56.8  | ≥39.3      |
| [10]      | 0.9–2.8        | 102           | 52–85  | 39.6–43.1  |
| [11]      | 3.5–6.0        | 53            | 51–64  | 8–41       |
| This Work | 1.0–3.0        | 100           | 55–66  | 40–42.6    |

### 4 Conclusion

A novel design strategy has been proposed to extend bandwidth for Class-J power amplifier in this work. A compact low-pass OMN is used. In order to broaden the bandwidth, an opened-sector microstrip transmission line is used instead of the parallel capacitor. The proposed amplifier is fabricated and 100% fractional bandwidth has been achieved with above 40 dBm output power and 55% drain efficiency.

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