# A 0.6–2.4 GHz Broadband GaN HEMT Power Amplifier with 79.8% Maximum Drain Efficiency

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**Abstract.** A highly efficient and broadband 10 W GaN HEMT power amplifier (PA) is presented, which employs the hybrid PA mode, transferring between continuous Class-F, continuous Class-B/J and continuous inverse Class-F. A GaN PA is designed and realized based on this mode-transferring operation using low-pass filter output matching network. The maximum theoretical efficiency of this hybrid continuous modes PA is more than 78.5%. Specifically, the operating bandwidth is determined by the low pass filter output matching network and the theoretical bandwidth can achieved multi-octave. The proposed design strategy is experimentally verified by a 0.6–2.4 GHz PA design with 79.8% maximum drain efficiency and 10 W output power. The footprint of the fabricated PA is 75 mm × 40 mm.

**Keywords:** Power amplifier · Continuous Class-F · Hybrid continuous modes · Low-pass filter

## 1 Introduction

The advantages of highly efficient power amplifiers (PAs) have been introduced in the literatures and a class-F PA is more attractive to reach this target. As is explained in [1], the square voltage waveform of the ideal Class-F PA operation is produced by odd harmonics and the half-sinusoidal current waveform is the result of fundamental and even harmonics. Given the condition with symmetrical drain current and voltage waveforms, drain efficiency of the ideal Class-F operation can be able to reach 100%. However, the Class-F PA has a main problem of narrow bandwidth. Since the Class-F PA has the intrinsic sensitivity to the load, it has been very difficult to design the Class-F PA with wide bandwidth in principle. A broadband Class-F PA achieving power added efficiency above 64% from 575–915 MHz is proposed in [2].

The harmonic load-pull technique was used to design the PA, where the output matching network was designed primarily to achieve quasi-optimal loads


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at the fundamental and second harmonics. The continuous Class-F working mode and its extension modes have been presented to broaden the design range of Class-F, which is proposed in [3] proving that the PA bandwidth can be widened. With the help of output capacitance $C_{DS}$ of the nonlinear transistor model and simplified real frequency method, PA design can be attributed to the research of broadband fundamental matching [4].

## 2 PA Design Methodology

The bandwidth of the broadband PAs proposed in the literature can reach more than 50%. However, achieving efficiency more than 60% at RF frequency depends largely on the precise control of the first three harmonics in output stage, which will lead to low efficiency performance when the bandwidth is over more than an-octave. In our work a novel technique of designing PA with octave bandwidth and high efficiency is proposed. A hybrid PA mode which comprised of continuous Class-B/J, continuous Class-F and continuous inverse Class-F is utilized to design and implement a 0.6 GHz–2.4 GHz PA, and a low-pass filter topology is adopted to design the output matching network.

The normalized drain currents of continuous Class-B/J PAs are defined by Eq. (1), the same as Class-B power amplifier. The normalized drain voltages of Class-B/J PAs are shown in Eq. (2).

$$i_{CBJ}(\theta) = \frac{1}{\pi} + \frac{1}{2}cos(\theta) + \frac{2}{3\pi}cos(2\theta) + ... \tag{1}$$

$$v_{CBJ}(\theta) = (1 - cos\theta)(1 - \gamma sin\theta), -1 \le \gamma \le 1 \tag{2}$$

The normalized drain currents of continuous Class-F PAs are also defined by Eq. (1). The normalized drain voltages of Class-F PAs are shown in Eq. (3).

$$v_{CF}(\theta) = (1 - \frac{2}{\sqrt{3}}cos\theta + \frac{1}{3\sqrt{3}}cos3\theta)(1 - \gamma sin\theta), -1 \le \gamma \le 1 \tag{3}$$

The normalized drain currents of continuous inverse Class-F are defined by Eq. (4). The normalized drain voltages of inverse Class-F are shown in Eq. (5).

$$i_{CIF}(\theta) = [0.37 - 0.43cos\theta + 0.06cos(3\theta)](1 - \gamma sin\theta), -1 \le \gamma \le 1 \tag{4}$$

$$v_{CIF}(\theta) = 1 + \sqrt{2}cos\theta + \frac{1}{2}cos(2\theta) \tag{5}$$

The normalized voltages and currents of continuous Class-B/J and continuous Class-F based on equations are shown in Fig. 1. The blue curves show continuous Class-F voltage waveforms, the red curves show continuous Class-B/J voltage waveforms, and the black curve represents current waveform. The normalized currents and voltages of continuous inverse Class-F based on equations are shown in Fig. 2. The blue curves represent voltage waveforms, and the black curve represents current waveform.

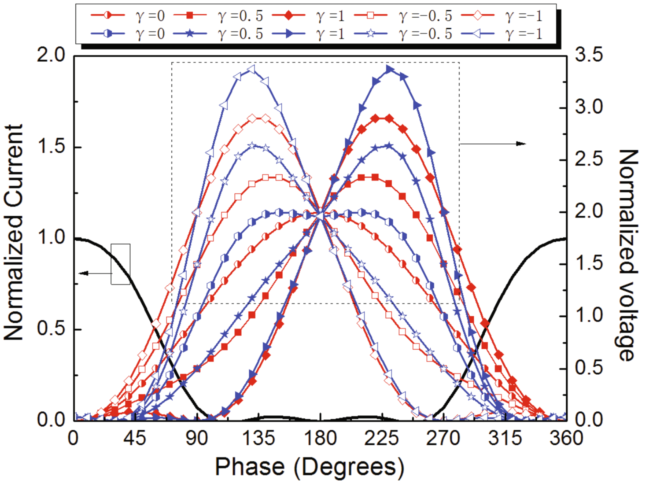


**Fig. 1.** Theoretical voltage and current waveforms of continuous Class-B/J and continuous Class-F (Color figure online)

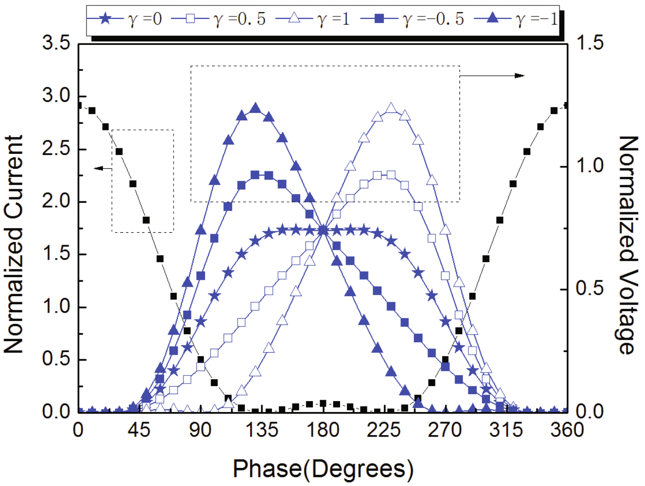


**Fig. 2.** Theoretical voltage and current waveforms of continuous inverse Class-F (Color figure online)

The continuous Class-B/J maintains the same DC voltage and fundamental voltage components as Class-B, therefore continuous Class-B/J can achieve equal power and efficiency of class-B. The ideal efficiency of continuous Class-B/J is 78.5% [4]. The above Eqs. (1) and (3) are used to prove that the theoretical drain efficiency of this continuous Class-F is able to achieve 90.7% [5]. The above Eqs. (4) and (5) are used to prove that the theoretical drain efficiency of this continuous inverse Class-F is able to achieve 81.85% [6].

Provided different $\gamma$ values, different fundamental impedances can be presented with a larger range. Consequently, an ideal bandwidth is achieved by the combination kit of continuous PA modes, continuous Class-B/J, continuous Class-F and continuous inverse Class-F. The fundamental impedances can be calculated by Eq. (6).

$$\begin{aligned} Z_{CBJ} &= R_L + jR_L\gamma \\ Z_{CF} &= \frac{2}{\sqrt{3}} + jR_L\gamma \\ Z_{CIF} &= \frac{1}{0.43\sqrt{2} + j0.37\sqrt{2}\gamma} R_L \end{aligned} \tag{6}$$

Figure 3 illustrates the fundamental impedances spaces of continuous Class-B/J, continuous Class-F and continuous inverse Class-F. The fundamental impedances spaces of this hybrid PA mode are further enlarged compared to conventional continuous PA modes.

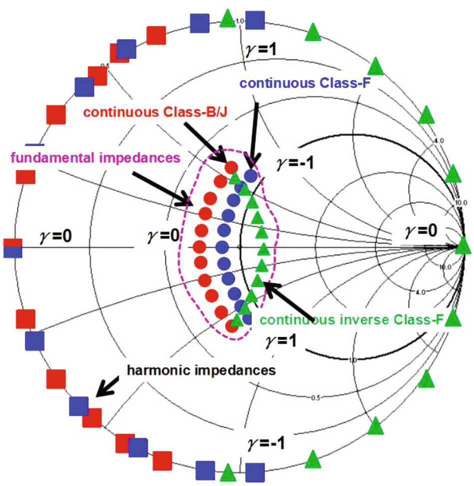


**Fig. 3.** The first three calculated harmonic impedances of continuous Class-B/J, continuous Class-F and continuous inverse Class-F in the smith chart

## 3 Matching Network Design

To realize broadband PAs needs a proper matching network. Literature [7,8] present the low-pass filter topology based on transmission line to achieve broadband and highly efficient PA. As is shown in Fig. 4, the output matching circuit and frequency response of the PA are given. Frequency response curve shows that the PA is working in continuous Class-B/J state at frequency point $f_1$, inverted Class-F state at frequency point $f_2$ and Class-F state at frequency point $f_3$.

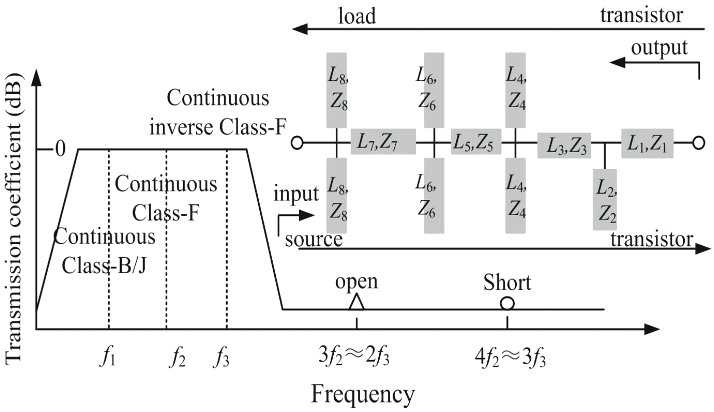


**Fig. 4.** Low-pass filter matching network for broadband PA using stepped transmission line transformer and the frequency response of the hybrid continuous PA mode

A bold improvement method is proposed that the second harmonic open circuit termination of continuous inverse Class-F PA and the third harmonic open circuit termination of continuous Class-F PA are both achieved by the output matching network. Thus, $3f_2$ is approximately equal to $2f_3$. Simultaneously, the third harmonic short circuit termination of continuous inverse Class-F PA and the fourth harmonic short circuit termination of continuous Class-F PA are also both achieved by the output matching network. It is obvious from the frequency response that $4f_2 \approx 3f_3$. The conversion of this working mode is able to broaden the bandwidth of PAs to a great extent. It is shown in the output matching circuit that high impedance transmission line can be utilized to be equivalent to inductance and low impedance open short wires is equivalent to capacitance, thus forming a third order low-pass filter matching circuit.

The input and output matching networks adopt stepped transmission line transformer and harmonic matching topology. In this design method, the input stepped transmission line transformer is applied to matching input impedance of the transistor to $50\,\Omega$ at fundamental frequency. The complete schematic of the PA, including input and output matching networks, is shown in Fig. 5. In order to obtain the impedance trajectories of the output matching network at I-gen plane in the smith chart, the approximated equivalent network of device output

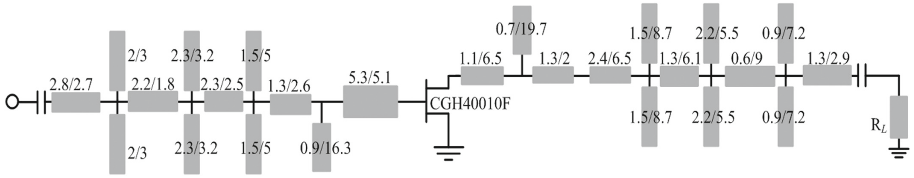


**Fig. 5.** Complete schematic with the dimensions of input and output matching network of the designed PA

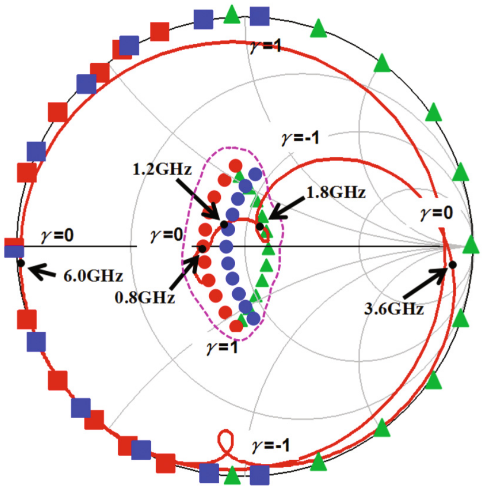


**Fig. 6.** Harmonic impedance trajectories of output matching network on I-gen planes in the smith chart

parasitic for CGH40010F is simulated by ADS. The fundamental impedance trajectories of the range from 0.6 GHz to 2.4 GHz are shown in Fig. 6.

From Fig. 6, the second and third harmonic terminals of continuous inverse Class-F are both at the optimal places, while the third and fourth harmonic terminals of continuous Class-F deviate from to the optimal places. However, great fundamental impedance matching status is obtained.

## 4 PA Design and Fabrication

The proposed PA is simulated with a constant drain supply voltage $V_{DD} = 28\,\mathrm{V}$ and the gate bias voltage $V_{gg} = -2.5\,\mathrm{V}$ which represents a bias condition of a conventional Class B amplifier. The optimum performance of continuous Class-B/J, continuous Class-F and continuous inverse Class-F have been achieved at frequency points of 0.9 GHz, 1.4 GHz and 2.1 GHz respectively. The substrate of the designed PA is RO4003C. American Technical Ceramics (ATC)

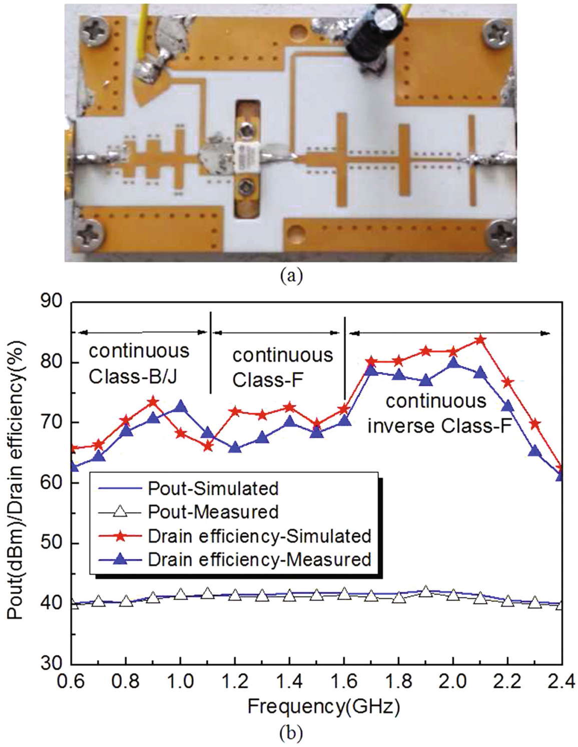


**Fig. 7.** Circuit and results. (a) the Fabricated PA circuit. (b) the simulated and measured drain efficiencies and output power of designed PA with respect to frequency

100A is used for DC-block, while ATC 100B and Panasonic electrolytic capacitors are used for bias line resonant capacitors. The footprint of the fabricated PA is 75 mm × 40 mm. Figure 7(a) shows the fabricated circuit of the design.

The PA is measured under the excitation of a single-tone continuous wave sweeping from 0.6 GHz to 2.4 GHz with the step size of 100 MHz. The simulated and measured drain efficiency in the whole frequency range are shown in Fig. 7(b). The measured drain efficiency range is from 61.1% to 79.8%, whose average value is about 70%. The output power are also taken into account and tested, as is shown with the power curves shown in Fig. 7(b). The output power is about 39.7 dBm to 41.6 dBm within the whole sweeping frequency band. An average gain of around 10 dB is measured.

The comparison between our work and some other recent contemporary broadband PA results is shown in Table 1, including bandwidth, output power, drain efficiency and PA mode. It can be seen from Table 1 that our work shows a great bandwidth performance due to the high operating frequency band of the designed PA. We attribute this excellent performance to the combined utilization of continuous Class-B/J, continuous Class-F and continuous inverse

**Table 1.** Broadband PA comparison with other researches

| Ref | Bandwidth (GHz, %) | Power (W) | Drain Efficiency (%) | PA mode |
|---|---|---|---|---|
| 2009 [4] | 1.4–2.6, 60 | 9–11.5 | 60–70 | Class-J |
| 2012 [7] | 1.45–2.45, 51 | 11–16.8 | 70–81 | Continuous Class-F |
| 2013 [9] | 0.53–1.33, 87 | 8–13.8 | 70–87 | Continuous Class-F |
| 2014 [10] | 1.6.4–2.7, 51 | 10.2–17.8 | 70.3–81.9 | SCM |
| 2016 [11] | 2.4–3.9, 47.6 | 9.2–13.8 | 62.2–74.7 | SICM |
| This work | 0.6–2.4, 120 | 9.3–14.4 | 61.1–79.8 | Hybrid PA mode |

Class-F modes, and to the fact that the novel stepped transmission-line transformer is employed to optimize fundamental impedance and control the harmonic impedance directly.

## 5 Conclusion

A high efficiency broadband hybrid PA mode based on modified harmonic controlled network is presented. Both the multistage transmission line transformer and harmonic tuning circuits are used at the output matching network to increase the drain efficiency and broaden the bandwidth of the PA. The optimum performance of continuous Class-B/J, continuous Class-F and continuous inverse Class-F have been achieved at frequency points of 0.9 GHz, 1.4 GHz and 2.1 GHz respectively. The PA has achieved wide bandwidth of 0.6–2.4 GHz, with 61.1%–79% drain efficiency, 10 dB gain, and 10 W output power within the bandwidth.

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## References

1. Krauss, H.L., Bostian, C.W., Raab, F.H.: Solid State Radio Engineering. Wiley, New York (1980)
2. Butterworth, P., Gao, S., Ooi, S.F., Sambell, A.: High efficiency Class F power amplifier with broadband performance. Microw. Opt. Technol. Lett. **44**(3), 243–247 (2005)
3. Carrubba, V., Clarke, A.L., Akmal, M., et al.: On the extension of the continuous Class-F mode power amplifier. IEEE Trans. Microw. Theor. Tech. **59**(5), 1294–1303 (2011)
4. Wright, P., Lees, J., Benedikt, J., Tasker, P.J., Cripps, S.C.: A methodology for realizing high efficiency Class-J in a linear and broadband PA. IEEE Trans. Microw. Theor. Tech. **57**(12), 3196–3204 (2009)

5. Carrubba, V., Clarke, A.L., Akmal, M.J., et al.: The continuous Class-F mode power amplifier. In: 40th European Microwave Conference, pp. 1675–1677. IEEE Press, Paris (2010)
6. Carrubba, V., Clarke, A.L., Akmal, M., Lees, J., Benedikt, J., Cripps, S.C., Tasker, P.J.: Exploring the design space for broadband pas using the novel continuous inverse Class-F mode. In: 41st European Microwave Conference, pp. 333–336. IEEE Press, Manchester (2011)
7. Tuffy, N., Guan, L., Zhu, A., Brazil, T.J.: A simplified broadband design methodology for linearized high-efficiency continuous Class-F power amplifiers. IEEE Trans. Microw. Theor. Tech. **60**(6), 1952–1963 (2012)
8. Chen, K., Peroulis, D.: Design of highly efficient broadband Class-E power amplifier using synthesized low-pass matching networks. IEEE Trans. Microw. Theor. Tech. **59**(12), 3162–3173 (2011)
9. Lu, Z., Chen, W.: Resistive second-harmonic impedance continuous Class-F power amplifier with over one octave bandwidth for cognitive radios. IEEE J. Emerg. Sel. Topics Circuits Syst. **3**(4), 489–497 (2013)
10. Chen, J., He, S., You, F., Tong, R., Peng, R.: Design of broadband high-efficiency power amplifiers based on a series of continuous modes. IEEE Microw. Wirel. Compon. Lett. **24**(9), 631–633 (2014)
11. Shi, W., He, S., Li, Q.: A series of inverse continuous modes for designing broadband power amplifiers. IEEE Microw. Wirel. Compon. Lett. **26**(7), 525–527 (2016)