LETTER
IEICE Electronics Express, Vol.14, No.9, 1–7

A broadband microwave GaN HEMTs class EF_3 power amplifier with π-type network

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Abstract: A GaN HEMTs class EF_3 power amplifier (PA) with π-type network for broadband operation is presented in this paper. The π-type network is constructed by shunt capacitance, series inductance and finite dc-feed inductance, where the series inductance includes the parasitic inductance effects of transistor. As a result, the topology can make full use of the parasitic effects of transistor to raise the operation frequency. Moreover, it is found that this topology can also increase the frequency bandwidth. For demonstration purpose, a PA prototype based on the topology is fabricated. Experimental results show that the amplifier can operate from 2.9 GHz to 4.0 GHz (fractional bandwidth 31.8%) with a measured drain efficiency higher than 67%, and the output power is greater than 37.4 dBm. The proposed structure can be a good candidate for design of high efficiency and broadband class E power amplifiers.

Keywords: class EF_3, power amplifier, GaN HEMT, π-type network

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

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DOI: 10.1587/elex.14.20170260
Received March 17, 2017
Accepted April 3, 2017
Publicized April 19, 2017
Copyedited May 10, 2017

IEICE Electronics Express, Vol.14, No.9, 1–7

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1 Introduction

One of the most important aspects of the power amplifier (PA) is efficiency. By increasing the efficiency, PA will consume less supply power and require less heat sinking, allowing a reduction of battery size and an increase of battery life. The

DOI: 10.1587/elex.14.20170260
Received March 17, 2017
Accepted April 3, 2017
Publicized April 19, 2017
Copyedited May 10, 2017

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switch mode class E PA is a competitive candidate for a high efficiency PA among state of art wave-engineering techniques [1, 2].

In the switch mode class E PA, the transistor operates as an on/off switch. The waveforms of the current and voltage in time domain are such that high current and high voltage do not occur simultaneously, which minimizes the power dissipation and maximizes the power amplifier efficiency. The class E with finite dc-feed inductance is one topology of class E PA, but the output parasitic inductance of the transistor is neglected. This is not suitable in S band because the parasitic series inductance can be one-tenth of the dc-feed finite inductance. So we present the topology of class E PA with the π-type network that includes shunt capacitance, series inductance and finite dc-feed inductance. This topology takes full advantages of the parasitic series inductance to obtain the optimal load R and wider bandwidth.

High efficient operation of PA can be obtained by polyharmonic modes [3], which was used in class F or inverse class F PA [4]. The mixed mode class EF [5] or E/F [6] operation provides a tradeoff between the simplicity of class E and benefits of class F or inverse class F. Class E/F achieve zero voltage and zero voltage derivative switching conditions when even harmonics are open circuits and odd harmonics are short circuits. In contrast, class EF achieve zero voltage and zero voltage derivative switching conditions when even harmonics are short circuits and odd harmonics are open circuits. For broadband PA, it is difficult to control all the harmonics, but the second and third harmonics have an important impact on the efficiency. Class EF_2 PA achieve zero voltage and zero voltage derivative switching conditions when the second harmonic is short circuit. Class EF_3 PA achieve zero voltage and zero voltage derivative switching conditions when the second harmonic is short circuit and the third harmonic is open circuit.

In this paper, a class EF_3 power amplifier with π-type network is presented. The π-type network is used to broaden the bandwidth. The short circuit of second harmonic and open circuit of third harmonic can significantly improve the efficiency.

2 Design of class EF_3 power amplifier with π-type network

Fig. 1 shows the basic circuit configuration of a class E power amplifier with π-type network. The π-type network includes a shunt capacitance C_{ds}, a series inductor L_1 and a finite dc-feed inductance L_2.

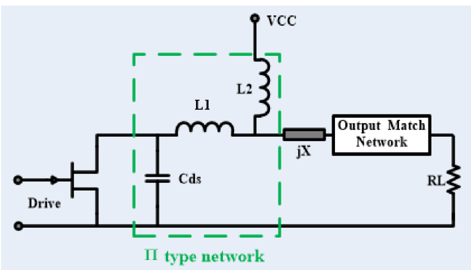

Fig. 1. Basic circuits of class E PA with π-type network

Fig. 2 shows the effects of series inductance L_1 on the normalized load resistor RP_{out}/V_{cc}^2 of class E amplifier with π-type network, where $\omega_0 = 1/\mathrm{sqrt}(C_{ds}L_2)$,

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$\chi = \omega/\omega_0$, $\alpha = L_1/L_2$, ω is the operating frequency, P_{out} is the output power, V_{CC} is the drain voltage, and R is the load resistor. The largest load resistor is $R_{max} = (1.3633V_{cc}^2)/P_{out}$. The load resistor R is adjustable.

(1) If $R_{max} < 50$ ohm, the series inductance $(L_1)_{opt1}$ should be the smallest which is the sum of the output parasitic inductance and the bonding wire inductance, $\chi_{opt1} = 0.681$, $L_2 = (0.681^2)/(\omega^2 C_{ds})$, $\alpha = (L_1)_{opt1}/L_2$. From Fig. 2, we can see that there always exists an optimal value $\chi_{opt2}(<0.681)$ for the load resistor to obtain the maximum value, which gives $(L_2)_{opt1} = (\chi^2{}_{opt2})/(\omega^2 C_{ds})$.

(2) If $R_{max} > 50$ ohm, there always exist optimal values $\alpha_{opt}(>0)$ and $\chi_{opt3}(<0.681)$ for the load resistor to obtain the optimal value $(R_{max})_{opt} = 50$ ohm, which gives $(L_2)_{opt2} = (\chi^2{}_{opt3})/(\omega^2 C_{ds})$, $L_1 = \alpha_{opt}(L_2)_{opt}$.

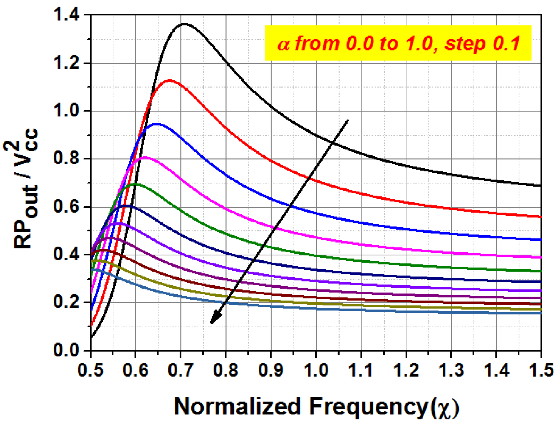

Fig. 2. Effects of series inductance L_1 on the normalized load resistor RP_{out}/V_{cc}^2 of class E amplifier with π-type network

A 0.25 µm gate length GaN HEMT [7, 8] with 1.25 mm total gate-width is used in our design. For this transistor, the parasitic output capacitance [9, 10] C_{ds} is 0.254 pF and the parasitic output inductance L_{para} is 0.15 nH. The inductance L_{wire} induced by bonding wire is 0.8 nH. The drain voltage $V_d = 28$ V, the output power $P_{out} = 8$ W and the center frequency $f_0 = 3.1$ GHz have been selected. Then, the largest load resistor is $R_{max} = (1.3633V_{cc}^2)/P_{out} = 133$ ohm, and the optimal values are $\alpha_{opt} = 0.5$ and $\chi_{opt3} = 0.58$. For the load resistor R to obtain the optimal value $(R_{max})_{opt} = 50$ ohm, we get $L_2 = 3.49$ nH and $L_1 = 1.745$ nH. The inductance L_1 and L_2 are realized by the high impedance microstrip transmission line.

Typically, the nonlinear class E PA achieve high efficiency when the output power gain at 3 dB or 4 dB compression point. So it is necessary to suppress output harmonic [3] to improve efficiency. The proposed schematic of a transmission line class EF_3 with π-type network is shown in Fig. 3. Both low impedance at the second harmonic and high impedance at the third harmonic are created at the device output by using short-circuited stub TL and open circuit stub.

In the input network, appropriate second harmonic source impedance [11] can enhance the efficiency of PA. The low pass input network in [12] is adopted for operation frequency. Shunt resistance R_1, capacitance C_2 and resistance R_2 in the input network are used to improve the low frequency stability.

DOI: 10.1587/elex.14.20170260
Received March 17, 2017
Accepted April 3, 2017
Publicized April 19, 2017
Copyedited May 10, 2017

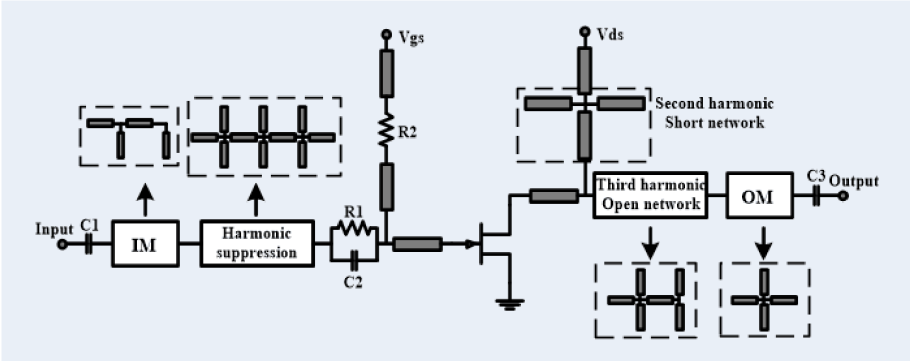

Fig. 3. Class E PA with π-type network

Fig. 4 shows the simulated waveforms of the switch voltage and current in time domain when the input power is 23 dBm at 2.7 GHz. It can be found that the maximum of the switch voltage is 78 V, the maximum of switch current is 0.8 A. The switch voltage and current waveforms are almost not overlapping.

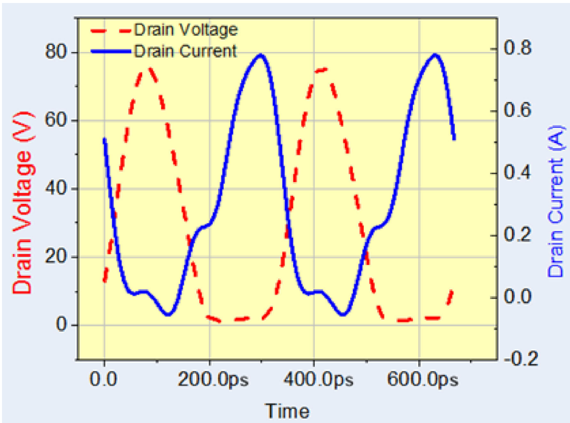

Fig. 4. Waveform of the switch voltage and current at time domain at 2.7 GHz when Vds = 28 V and Vgs = −3 V

3 Implementation and experimental results

Fig. 5 shows the photo of the fabricated class EF_3 PA with π-type network. Fig. 6 shows the measured drain efficiency (DE), power added efficiency (PAE), output power (Pout) and Gain versus the input power at 3.0 GHz for continuous wave (CW) input signal. The maximum PAE is 63.4% for the input power 26 dBm when $V_{cc} = 28$ V, $V_g = -3.0$ V.

Fig. 7 shows the measured second and third harmonic suppressions within the bandwidth. The maximum second harmonic is −21.5 dBc at 4.0 GHz, and the minimum second harmonic is −42.35 dBc at 3.3 GHz. Most of the second harmonics are below −25 dBc. The maximum third harmonic is −28.8 dBc at 2.9 GHz, and the minimum third harmonic is −60.87 dBc at 3.6 GHz. Most of the third harmonics are below −35 dBc.

Fig. 8 shows the simulated and measured behavior of the DE, PAE, output power and output power gain according to the operating frequency at input power

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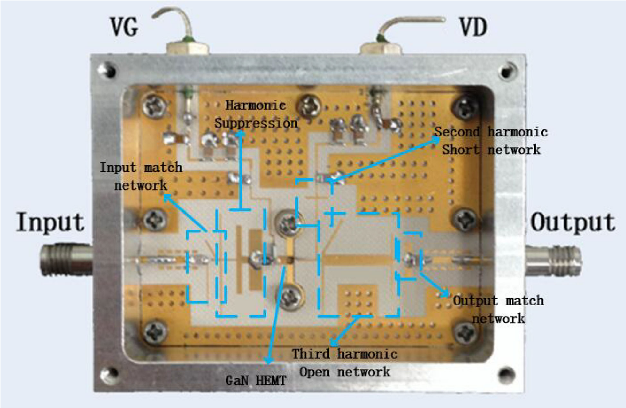

Fig. 5. Photo of Fabricated class EF_3 PA with π-type network

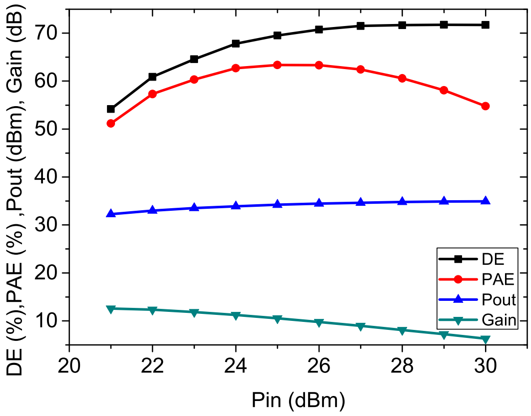

Fig. 6. Measured DE, PAE, Pout and Gain versus input power at 3.0 GHz

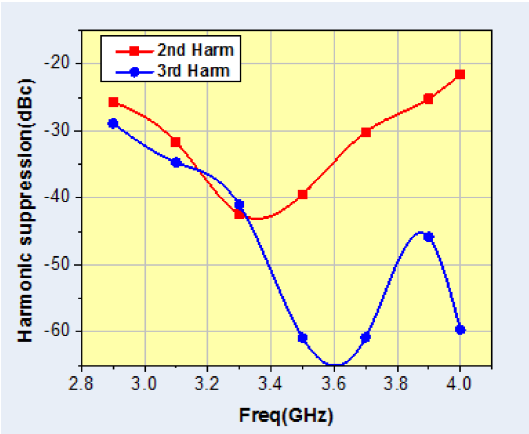

Fig. 7. Measured second and third harmonic

of 29 dBm. It can be seen that the PAE is 58.8%~62.9%, the DE is 67%~77.9%, the output power gain is larger than 7.16 dB, the output power is more than 37.4 dBm between 2.9 GHz and 4.0 GHz (31.8% fractional band width (FBW)).

The performances are compared with the published data for the PAs operating around 2.5 GHz and summarized in Table I. The results show that our designed PA provides better performance at higher frequency.

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Accepted April 3, 2017
Publicized April 19, 2017
Copyedited May 10, 2017

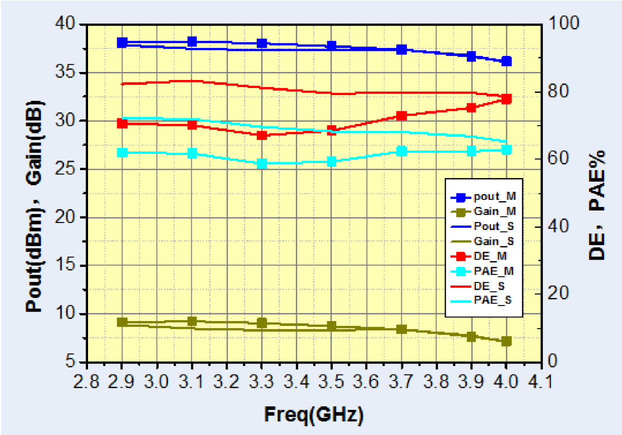

Fig. 8. Simulated and measured frequency dependence of DE, PAE, Pout and Gain characteristics.

Table I. Comparison of GaN PA

Work	GHz/FBW (%)	DE (%)	Pout (dBm)
2009[13]	2.0–2.5(22.2%)	>74	>38.5
2012[14]	1.6–2.2(31.5%)	>55	>40
2014[15]	1.9–2.7(34.7%)	>58	>40
2014[16]	1.7–2.8(48.8%)	>58	>43
2016[17]	1.4–2.7(63.4%)	>63	>39.7
This work	2.9–4.0(31.8%)	>67	>37.4

4 Conclusion

A GaN HEMT class EF_3 power amplifier with π-type network is designed, fabricated and measured. The measured and simulated data are found in good agreements. It can operate at higher frequency range than existing designs with satisfying drain efficiency and output power. The proposed structure can be a good candidate for broadband class E power amplifiers.

Acknowledgements

This work was supported in part by the National Natural Science Foundation of China (Grant No. 61474042) and in part by the National Key Project of Science and Technology.

DOI: 10.1587/elex.14.20170260
Received March 17, 2017
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Publicized April 19, 2017
Copyedited May 10, 2017