A Very Low Distortion High Efficiency Class-F Power Amplifier at 900 MHz

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Abstract- **This paper presents a novel class-F power amplifier for mobile applications in which with a proper harmonic tuning structure the need for an extra filtering section is eliminated. A class-F power amplifier employing a GaN HEMT device has been designed, fabricated and measured at 900 MHz. The fabricated circuit achieves an excellent harmonic-suppression level and the total harmonic distortion is around 1.2%. It overcomes the narrow band performance of class-F power amplifiers, giving more than 70% efficiency over a 100 MHz bandwidth. Experimental results show that the amplifier is able to deliver 38.5 dBm output power while achieving the state-of-the-art PAE of 80.5% with a peak drain efficiency of 84%, and a power gain of 13.6 dB for an input power of 25 dBm. A good agreement between measurement and simulation results is observed for the proposed structure.**

I. INTRODUCTION

Power amplifiers (PAs) are the most important part in transmitter design because they consume most of transmitter DC power and if this consumption is high it leads to an undesired short battery lifetime. Therefore it is important to design high efficiency power amplifiers for mobile applications. Switching PAs like class-D, class-E/E^{-1}, and class-F/F^{-1} [1] have a minimum overlap between drain voltage and current waveforms, resulting in low DC power consumption and high efficiency. Transistor large output capacitance imposes low impedance at high-frequencies which decreases the efficiency of class-E PAs but its effect is negligible in class-F PAs due to the harmonically tuned output network. A class-F PA uses multiple resonators in its output matching network to obtain a half sine drain current waveform and square drain voltage waveform. In theory class-F can achieve 100% efficiency but in practice this figure is lowered due to the limited number of harmonics that can be tuned through the output matching network [2].

Depending on the application and frequency, the matching network (MN) can be designed with lumped [3] or distributed [4] elements. An example of lumped MN and its equivalent transmission-line MN for class-F/F^{-1} PAs is given in [5]. At microwave frequencies, transmission-line MNs are preferred because implementing lumped-element multi-resonators at these frequencies is difficult. Possible load MNs for class-F/F^{-1} PAs, designed specifically to overcome the effect of shunt capacitance and series inductance, are well illustrated in [6] and [7]. Studies in [4] show that harmonic termination has an inverse relation with the performance of the amplifier and second harmonic tuning has the most important effect.

In this paper a novel class-F PA topology is proposed employing an output MN that controls up to the third harmonic component independently from fundamental matching. With a proper harmonic tuning structure the need for an extra filtering section is eliminated and a very low harmonic distortion is achieved. The proposed topology designed and fabricated at 900MHz, exhibits a very high (state-of-the-art) drain efficiency and PAE. It also overcomes the narrow band behavior of class-F PAs. A Cree GaN HEMT with a breakdown voltage of 120V is used as active device to fulfill the high voltage breakdown and high power requirements.

Section II shows the proposed PA topology and a comparison with three other PAs from literature. Section III shows the simulation, fabrication and measurement results followed by the conclusion in section IV.

II. CLASS-F POWER AMPLIFIER DESIGN

In class-F PAs, the load impedance seen by the power transistor should be a short circuit at even harmonics, an open circuit at odd harmonics and the optimized value at fundamental frequency:

$$Z_1 = R_{\text{optimal}} \quad (1)$$

$$Z_{2n} = 0 \quad (2)$$

$$Z_{2n+1} = \infty \quad (3)$$

The proposed design is illustrated in Fig. 1 where transmission lines TL8, TL9, TL11 and TL12 match the power device to 50 Ω input for a high power transfer. In the input MN, TL10 grounded through a bypass capacitor, is λ/4 at fundamental frequency which provides an open circuit for RF signal, and has an electrical length of 180° at second harmonic which provides a short circuit to the second harmonic component. Resistors R_1, R_2 and R_3 are added to ensure that the circuit works under stable conditions.

Concerning the output MN, the proposed structure allows the control of several harmonics simultaneously but independently of each other. The output MN provides an open circuit to the third harmonic through TL1 and TL2, with lengths of λ/12 at fundamental frequency (Fig. 1(b)). At second harmonic, TL3 delivers low impedance to the right hand side of TL4 with an electrical length of Θ_1, as shown in Fig. 1(c). Transmission lines TL1, TL2 and TL4 together provide a short circuit condition at second harmonic. TL5, TL6 and TL7 create a π-shape MN which increases the design freedom for fundamental frequency helping the designer to improve the performance in terms of efficiency and output voltage waveform. The stub with a highest effect on the

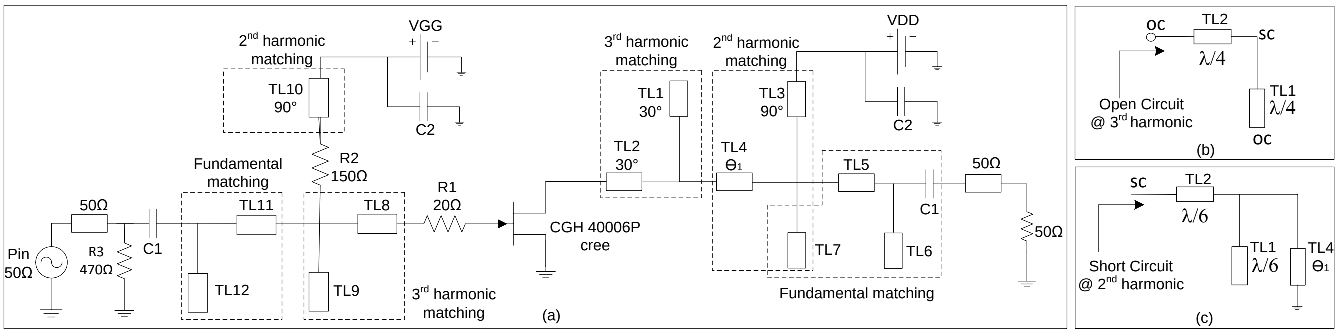


Fig. 1. (a) Proposed class-F PA, (b) output network at 3rd harmonic, (c) output network at 2nd harmonic

output waveform is TL7. This stub improves the output voltage waveform to present a perfect sinusoidal shape without distortion.

In practice, due to nonlinearities and parasitics of the active device (Cree CGH40006P), ideal short and open circuits do not necessarily lead to the best results. Therefore, to achieve the best performance, an accurate load matching for the output of transistor at fundamental and harmonic frequencies is required. Calculated from load-pull analysis, Z_{L1}, Z_{L2} and Z_{L3} are load impedances that result in an optimum performance at fundamental, second and third harmonics respectively. The calculated values are given in Table 1 and an output MN is designed to give these optimum impedances at the desired frequencies.

	Load impedance (Ω)
Z_{L1} (@ 900 MHz)	47.673 + j39.144
Z_{L2} (@ 1800 MHz)	2.31 - j13.121
Z_{L3} (@ 3600 MHz)	58.528 + j234.846

Table 1. Load Impedances for fundamental, second and third harmonic.

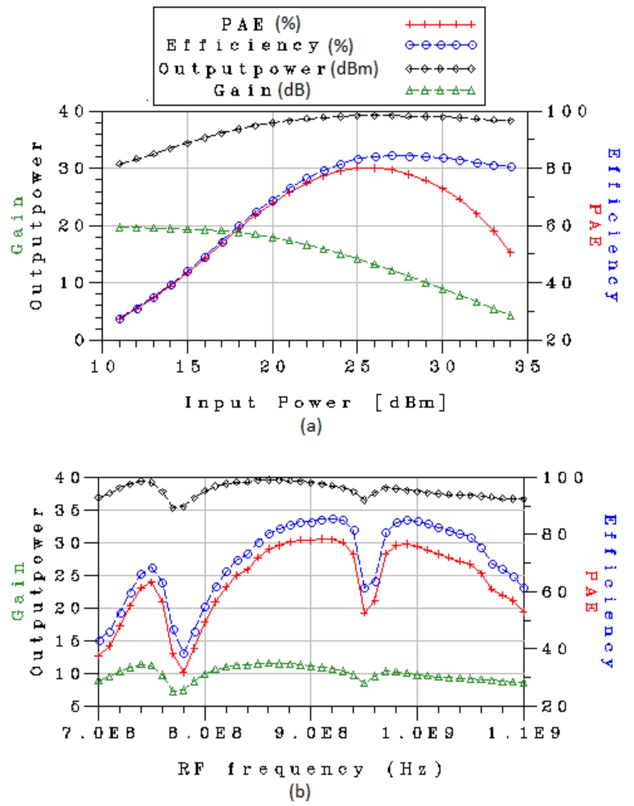


Fig. 2 Simulated output power, Gain, drain efficiency and PAE (a) versus input power, (b) versus RF frequency (V_{DS} = 28 V, V_{GS} = -2.8 V, f_0 = 900 MHz)

To evaluate the performance of the proposed topology, Large Signal S-parameter (LSSP), Harmonic Balance (HB) and Momentum simulations are performed using Agilent™ Advanced Design System (ADS). Simulation results of output power, gain, drain efficiency and PAE are plotted versus input power and RF frequency in Fig. 2(a) and Fig. 2(b) respectively. A peak PAE of 80.2%, drain efficiency of 83.5% and gain of 14.2 dB are obtained at output power of 39.2 dBm. Results versus frequency show that the amplifier is designed for the optimum value at the operating frequency. Also it can be seen that in a bandwidth from 810 MHz to 930 MHz it achieves a PAE higher than 60%.

The performance of the proposed topology (Fig. 1) is now compared to that of three class-F structures proposed in the literature. The output matching networks shown in Fig. 3 (a), (b) and (c) are retrieved from [6], [5] and [8] respectively. They have been designed and simulated to give best results at 900 MHz for the same power device under the same condition of our design. HB and LSSP simulations were carried out for these circuits and results are compared in Table 2, from which it can be seen that the structure proposed in this paper has the highest PAE, gain and output power. It also exhibits a good harmonic rejection up to fifth harmonic with good input and output matching.

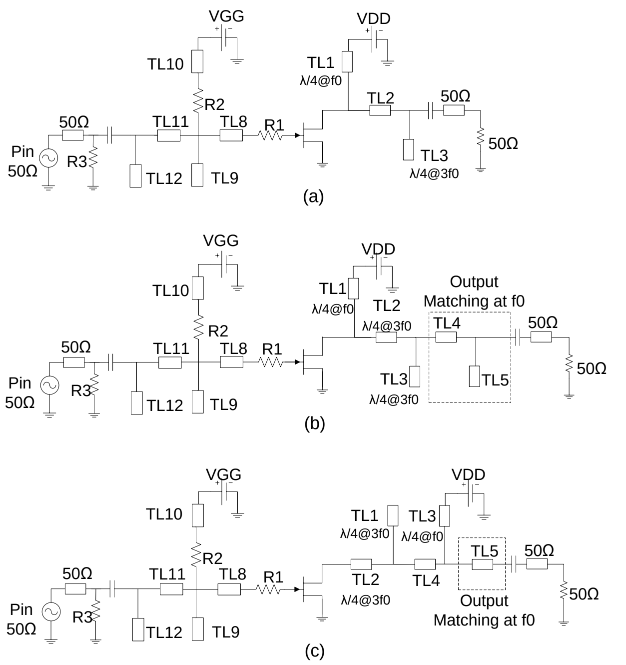


Fig. 3. Three class-F PAs, The output matching networks are retrieved (a) from [6], (b) from [5] and (c) from [8].

		Fig.1	Fig.3(a)	Fig.3(b)	Fig.3(c)
PAE (%)		80.2	73.20	79.57	78.37
η (%)		83.5	75.36	83.26	81.62
Gain (dB)		14.2	15.41	13.53	13.98
Pout (dBm)		39.2	40.4	38.5	38.9
Reflection coefficient	S11 (dB)	-14.6	-21	-18	-17
	S22 (dB)	-23.8	-6.8	-16.5	-19
Harmonic Rejection	$2f_0$ (dBc)	-46.77	-39	-48.46	-49
	$3f_0$ (dBc)	-46.83	-39.8	-48.3	-29.7
	$4f_0$ (dBc)	-68.6	-45	-48.29	-61.55
	$5f_0$ (dBc)	-49.24	-45.62	-58.94	-48.45

Table 2. Comparison of simulation results for the three circuits of Fig. 3

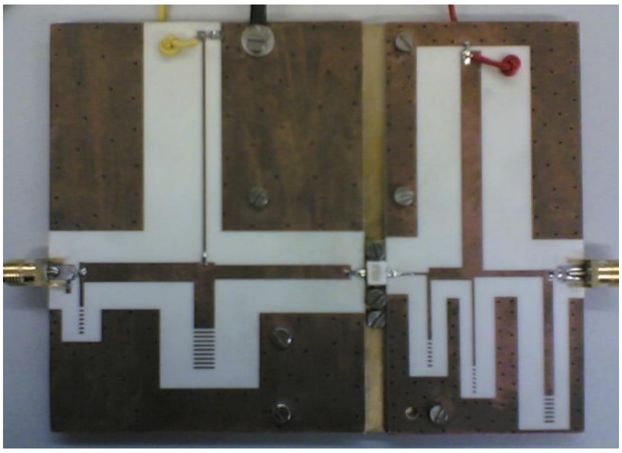


Fig. 4. Fabricated class-F PA

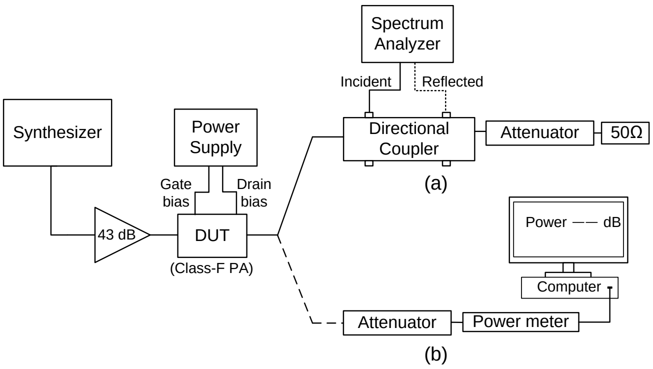
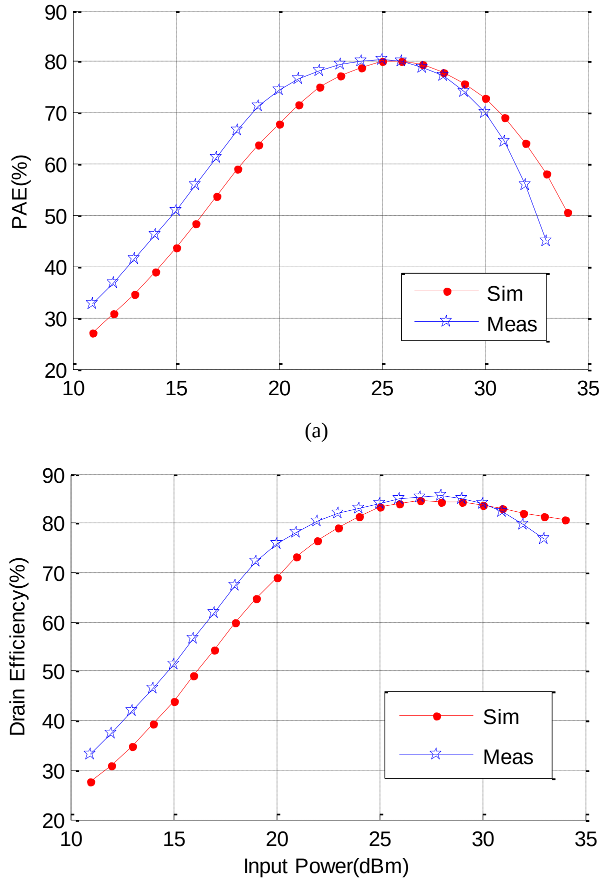


Fig. 5 Measurement setups

III. Fabrication And Measurements

In order to prove the simulation results, the proposed class-F PA is fabricated on a 1.524 mm RO4003 substrate. The implemented class-F PA and the measurement setup are depicted in Figs. 4 and 5 respectively. A synthesizer is used to generate the input signal and a pre-amplifier of 43 dB gain is used to increase the maximum input power available to the device under test (DUT). While the output power is accurately measured, using a calibrated attenuator and power meter [Fig. 5(b)], the input reflection coefficient and output spectrum are obtained using a directional coupler [Fig. 5(a)].

The measurement results from PAE and drain efficiency vs. RF frequency showed that the fabricated amplifier has the maximum values at a frequency of 875 MHz. Therefore, measurements are done with the transistor biased with gate voltage V_{GS} = -2.7 V and drain voltage V_{DS} = 30.2 V at f = 875 MHz to achieve the best results. Comparisons of simulation and measurement results are shown in Figs. 6 and 7. It can be seen that measurement results agree quite well with simulation results. Fig. 6 plots the measured and simulated PAE and drain efficiency results versus input power. The PA features a measured PAE of 80.5% and drain efficiency of 84% at an input power level of 25 dBm. Measured and simulated output power and gain results versus input power are shown in Fig. 7 where the measured gain and output power are 13.6 dB and 38.5 dBm (7 W) respectively.



(b)

Fig. 6. (a) Power Added Efficiency (PAE) and (b) Drain Efficiency vs. Input Power, Comparison between simulation and measurement results (V_{DS} = 30.2 V, V_{GS} = -2.7 V, f_0 = 875 MHz).

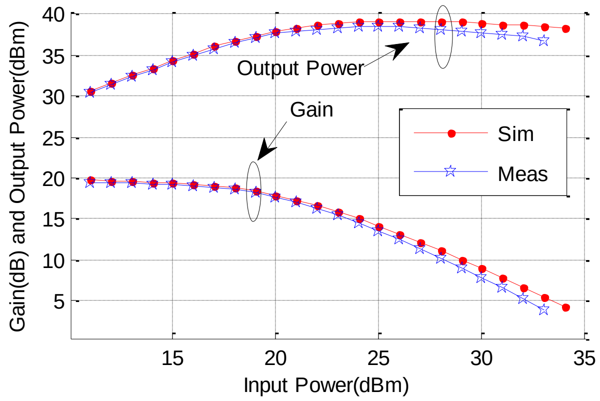


Fig.7. Output power and Gain vs. Input power, Comparison between simulation and measurement results (V_{DS} = 30.2 V, V_{GS} = -2.7 V, f_0 = 875 MHz).

The PA output voltage spectrum is shown in Fig. 8. The ratios between the fundamental output signal and harmonics are 33.45dB and 42.3dB for second ($2f_0$) and third ($3f_0$) harmonics respectively, showing that the proposed topology has the ability to reject harmonics while maintaining the high performance of the class-F PA and without the need for an extra filtering section. A low harmonic distortion is achieved and the total harmonic distortion (THD) is 1.2%. Using LSSP simulations, the PA large input reflection coefficient is simulated and compared to measured results in Fig. 9(a) ($|S_{11}|$) and Fig. 9(b) ($|S_{21}|$). Simulation and measurement are in good agreement and a good input matching is achieved.

An Infrared Camera was used to capture the thermal behavior of the circuit and the image is shown in Fig. 10. It can be seen that the circuit is thermally stable and the transistor doesn't get hot. The only point that gets hot is resistor R_1 but still it is in the acceptable range.

A comparison of this design and other in the literature is shown in Table 3. As it can be seen, the proposed structure achieves drain efficiency and PAE higher than other references while providing high output power and gain.

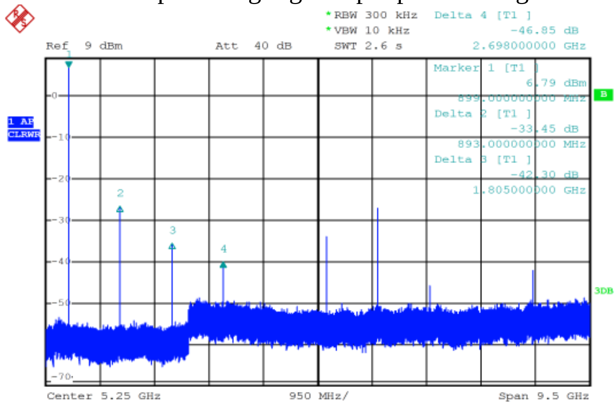


Fig. 8. Measurement results for load voltage spectrum

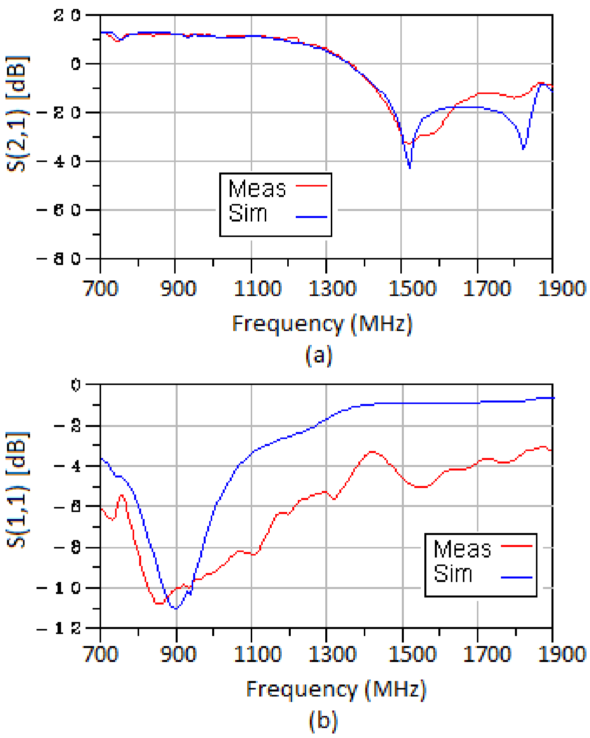


Fig. 9. Simulation and measurement results (a) $|S_{21}|$ and (b) $|S_{11}|$

	Device	Freq (GHz)	PAE (%)	η (%)	Gain (dB)	Pout (dBm)
[5]	LDMOSFET	0.5	-	76	17	43
[8]	pHEMT	2.45	70.4	-	9	21
[9]	GaN HEMT	3.54	62.4	69.4	-	52.5
[10]	GaN HEMT	2.655	75	77.7	14.8	40.5
[This work]	GaN HEMT	0.9	80.5	84	14.2	39.2

Table 3 comparison of this work with other works

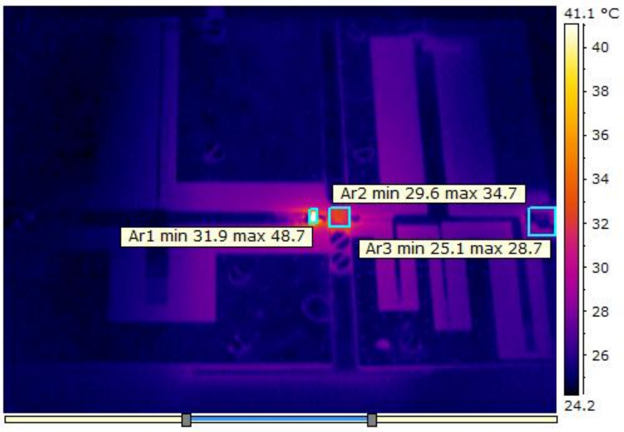


Fig. 10 Infrared measurement of the circuit heating

IV. Conclusions

A comprehensive study on the output matching network and performance of class-F PAs is presented in this paper. A novel class-F PA is proposed that controls fundamental matching independently from the harmonics by employing a pi-shape matching network increasing the degree of freedom in design. The proposed topology provides high harmonic rejection without the need for extra filtering sections. Measurement results show a high drain efficiency of 84% and PAE of 80.5% at 900 MHz. The measured output power and gain are 38.5 dBm and 13.6 dB respectively.

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