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# Highly efficient 2.7–2.9 GHz class-F and inverse class-F power amplifiers in GaN HEMT technology

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**Abstract:** In this letter, novel class-F and inverse class-F power amplifier (PA) topologies were proposed, simulated, realized and measured for 2.7–2.9 GHz frequency band by using Gallium Nitride high electron mobility transistor (GaN HEMT). Realizations are made on Rogers TMM3 dielectric material which has 0.381 mm thickness and 3.27 dielectric constant. Proposed class-F and inverse class-F PAs have 10 W (40 dBm) output power with 76% and 82% power added efficiency (PAE), respectively. Both PAs have state-of-the-art PAE performance compared to the PAs in the literature. Furthermore, the measurement results show that; under the same operation conditions, the inverse class-F PA has greater PAE than the class-F PA.

**Keywords:** class-F power amplifier, inverse class-F, GaN HEMT
**Classification:** Microwave and millimeter wave devices, circuits, and systems

## References

[1] F. H. Raab, "Class-F power amplifiers with maximally flat waveforms," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 11, pp. 2007–2012, Nov. 1997.
[2] F. H. Raab, "Class-E, class-C and class-F power amplifiers based upon a finite number of harmonics," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 8, pp. 1462–1468, Aug. 2001.
[3] S. Chen and Q. Xue, "A class-F power amplifier with CMRC," *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 1, pp. 31–33, Jan. 2001.
[4] S. Gao, P. Butterworth, A. Sambell, C. Sanabria, H. Xu, S. Heikman, U. Mishra, and R. A. York, "Microwave class-F and inverse class-F power amplifiers designs using GaN technology and GaAs pHEMT," *36th European Microw. Conf.*, pp. 1719–1722, Sept. 2006.
[5] K. Kuroda, R. Ishikawa, and K. Honjo, "High-efficiency GaN-HEMT class-F amplifier operating at 5.7 GHz," *38th European Microw. Conf.*, pp. 440–443, Oct. 2008.
[6] F. M. Ghannouchi, M. M. Ebrahimi, and M. Heloui, "Inverse class F power amplifier for WiMAX applications with 74% efficiency at 2.45 GHz," *IEEE Int. Conf. Communications*, pp. 1–5, June 2009.


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[7] Y. Xu, J. Wang, and X. Zhu, "Analysis and implementation of inverse class-F power amplifier for 3.5 GHz transmitters," *Proc. Asia Pacific Microwave Conf. (APMC)*, pp. 410–413, Dec. 2010.
[8] P. Saad, M. Nemati, M. Thorsell, K. Andersson, and C. Fager, "An inverse class-F GaN HEMT power amplifier with 78% PAE at 3.5 GHz," *39th European Microw. Conf.*, pp. 496–499, Oct. 2009.

## 1 Introduction

The class-F and inverse class-F amplifiers can be generally obtained by applying an even or odd harmonic trap circuit into the load network. Hence, the voltage waveform of a class-F amplifier is similar to a square wave and the inverse class-F amplifier has a half sinusoidal voltage waveform [1, 2, 3, 4, 5]. Unlike a class-F amplifier whose maximum voltage swing is less than two times the supply voltage value, the peak voltage of an inverse class-F amplifier can be larger than twice the supply voltage value at the expense of device stress relative to the devices breakdown voltage. Thus, peak voltage has often been difficult to realize with some transistors such as laterally diffused metal oxide semiconductor (LDMOS) and gallium arsenide (GaAs) devices. However, due to advances in wide bandgap semiconductor technology, particularly GaN HEMTs, a large rail voltage swing has become feasible; hence, allowing an inverse class-F amplifier with high efficiency to be achieved. As this breakdown voltage issue has been resolved, several papers in the literature have stated its superiority to a class-F amplifier for a given transistor [6, 7, 8]. In this paper, novel class-F and inverse class-F PA topologies were proposed for 2.7–2.9 GHz by using CGH40010F GaN HEMT from CREE. In experimental results, comparison of class-F and inverse class-F PAs was given in terms of output power, PAE and harmonic powers. Secondly, measured PAs were compared with the other class-F and inverse class-F PAs that have so far been reported in the literature.

## 2 Design of class-F and inverse class-F PA load networks

### 2.1 Proposed class-F load network topology

Ideally, for class-F PAs, it must have all of the odd harmonics terminated with an open circuit and all the even harmonics need a short circuit termination at the drain of the transistor. It is generally sufficient short circuit $2^{nd}$ order harmonic and open circuit $3^{rd}$ order harmonic [1]. Fig. 1 shows the proposed topology to realize the class-F conditions to get the higher efficiency by properly short and open circuit the $2^{nd}$ and $3^{rd}$ harmonics, respectively. Line-1 has 90° length at the fundamental frequency and 180° length at $2^{nd}$ harmonic; hence, it serves as a non–inverting microstrip line for $2^{nd}$ harmonic frequency. In that case, point-A and also point-B have low impedance. Line-2 selected as a high impedance microstrip line to guarantee impedance level of the point-B. Line-7 and line-6 have 30° length at fundamental frequency


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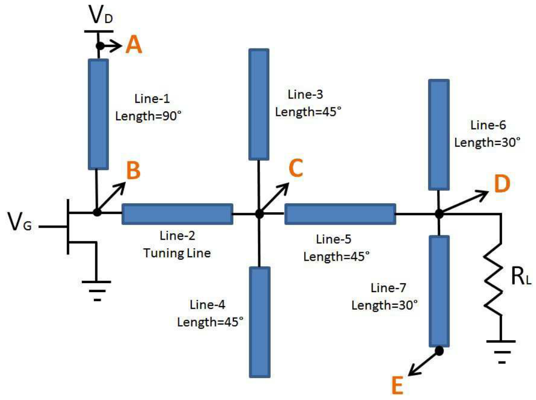


**Fig. 1.** The proposed class-F load network.

and 90° length at $3^{rd}$ harmonic. Therefore, they behave like an impedance inverter. Because point-E is open circuited, point-D has low impedance. With the aid of line-3, line-4, line-5 and the tuning line; drain of the transistor (point-B) has high impedance at the $3^{rd}$ harmonic frequency. Several optimizations were made with AWR Microwave Office to get the best class-F behavior.

## 2.2 Proposed inverse class-F load network topology

For the inverse class-F amplifier, harmonic conditions for the current and voltage waveform can be obtained from the following two conditions. The first, infinite impedance for even order harmonic frequencies is provided to remove even harmonics in the current waveform. The second, zero impedance for odd order harmonic frequencies is provided to remove odd harmonics in the voltage waveform. It is sufficient short circuit $3^{rd}$ order harmonic and open circuit $2^{nd}$ order harmonic to get inverse class-F behavior [3]. Fig. 2 shows the proposed topology to realize the class-F conditions in order to get the higher efficiency by properly open and short circuit the harmonics. Line-2 has 180° length at the $2^{nd}$ harmonic of the fundamental frequency and so it serves as a non–inverting line; hence, point-B is short circuited. Line-1 has 90° length at $2^{nd}$ harmonic therefore; it presents an impedance

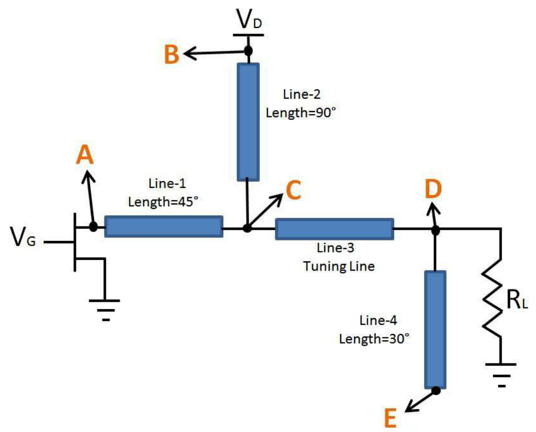


**Fig. 2.** The proposed inverse class-F load network.


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inverter behavior. Thus, point-A (drain of transistor) is open circuited. For $3^{rd}$ harmonic, line-4 has 90° length; hence, this line behaves as an impedance inverter and point-C is short circuited. With aid of the line-1 and line-3, the point-A is short circuited at $3^{rd}$ harmonic frequency. Since the line-2 is selected with high characteristic impedance, it presents very high impedance at the same point. Therefore, very high impedance for the $2^{nd}$ harmonic current is also provided at the drain of the transistor. Since the internal details of Crees large signal model were not available for reasons of confidentiality, parasitic components of GaN HEMT were unknown. Therefore, lengths of the lines were optimized for maximum efficiency and output power by using AWR Microwave Office. Furthermore, radial stubs whose lengths are 45° and 22.5° located on the input and output bias lines in order to shunt the circuits at $2^{nd}$ and $4^{th}$ harmonic frequencies, respectively.

## 3 Implementation and experimental results

Prototype boards are realized on a Rogers TMM3 PCB material whose dielectric constant is 3.27 and thickness is 0.381 mm. The photo of assembled class-F and inverse class-F prototypes are shown in Fig. 3 and Fig. 4, respectively. The total size of the PAs is 4.5 cm × 4.5 cm.

Gate and drain voltages were set to −3.2 V and 28 V for both PAs. Mea-

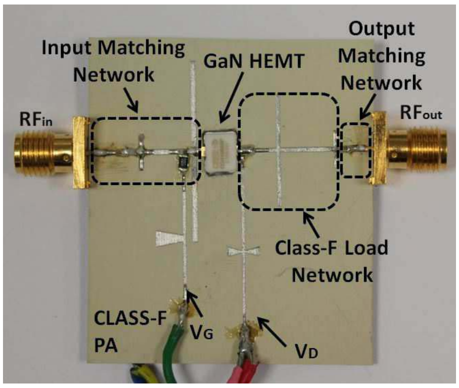


**Fig. 3.** Prototype of the class-F PA.

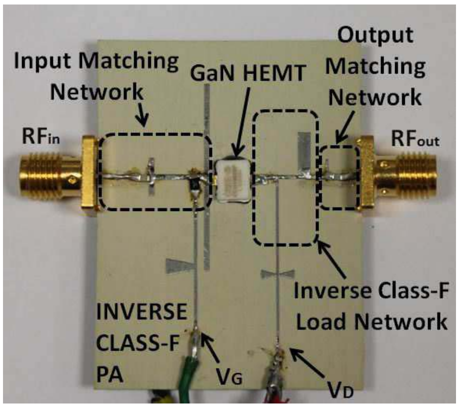


**Fig. 4.** Prototype of the inverse class-F PA.


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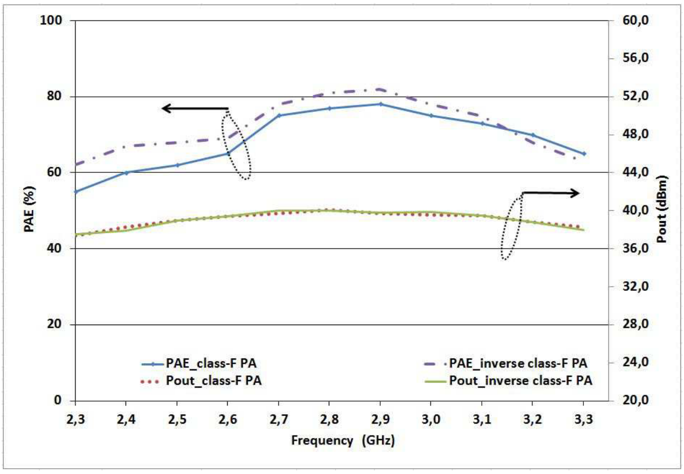


**Fig. 5.** Measured frequency response for the PAs.

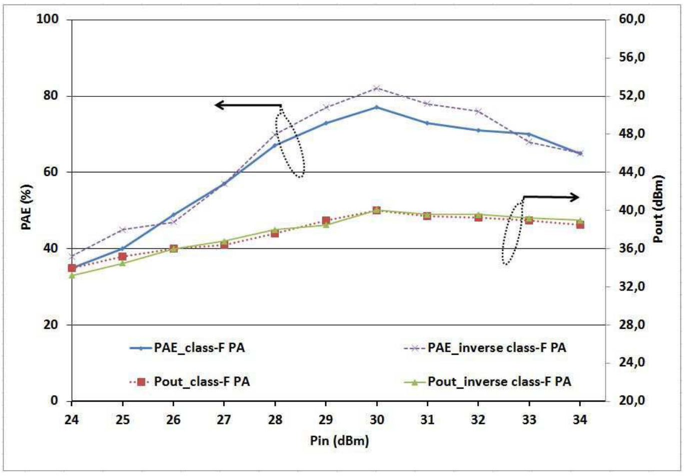


**Fig. 6.** Measured input-output power response and efficiency for PAs.

sured and simulated frequency responses, input-output power responses and efficiencies of the PAs are shown in Fig. 5 and Fig. 6. In the measurement, the RF signal is generated from a Rohde Schwarz SMIQ06B signal generator and amplified by the Mini-Circuits ZHL-16W-43+ preamplifier. Input and output RF powers were measured by using a Rohde Schwarz power meter. The PA prototype boards are driven with 30 dBm input power. From 2.7 to 2.9 GHz, class-F and inverse class-F PA have both output power of 40 dBm. Peak PAE of class-F PA and inverse class-F PA is 76% and 82%, respectively. In the same frequency range, the power gain remains for both PAs at 10 dB. Furthermore, temperature increment was measured by using laser thermometer and it was 15°C and 35°C after 30 minutes working with 10% duty cycle and continuous wave.

In order to compare the class-F and inverse class-F PA topologies in terms of harmonic powers, up to sixth of them were given in Fig. 7. As it can be seen from the figure below, class-F and inverse class-F PAs have nearly same degree harmonics up to sixth. Table I shows a summary of the measured


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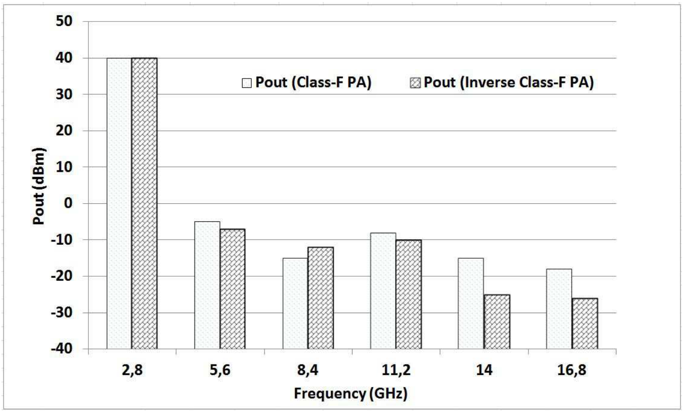


**Fig. 7.** Comparison of harmonic powers of the prototypes.

**Table I.** Comparison of characteristics.

| Ref. | Frequency (GHz) | Peak PAE% | Transistor | Class of PA |
|---|---|---|---|---|
| [3] | 2.4 | 74 | GaN HEMT | F |
| [4] | 2 | 50 | GaN HEMT | F |
| [5] | 5.7 | 68 | GaN HEMT | F |
| This work | 2.8 | 76 | GaN HEMT | F |
| [6] | 2.45 | 74 | GaN HEMT | Inverse F |
| [7] | 3.5 | 71 | GaN HEMT | Inverse F |
| [8] | 3.5 | 78 | GaN HEMT | Inverse F |
| This work | 2.8 | 82 | GaN HEMT | Inverse F |

results compared with other class-F and inverse class-F amplifiers that have so far been reported in the literature. As it can be seen in table, proposed PAs have state-of-the-art PAE performance among recently reported structures.

## 4 Conclusion

This letter proposes a 10 W class-F and inverse class-F PAs using GaN HEMTs for 2.7–2.9 GHz frequency band. Both PAs showed state-of-the-art PAE performances among realized PA topologies in the literature. For class-F and inverse class-F PA comparison, except for the PAE, they have almost the same performance at the saturated region. The proposed inverse class-F PA has superior PAE performance (82%) over the proposed class-F PA (76%).


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