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Highly efficient class-F power amplifier with digital predistortion for WCDMA applications

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Abstract: A digital predistorted class-F power amplifier (PA) using Cree GaN HEMT CGH40010 operating at 2.12 GHz is presented to obtain high efficiency and excellent linearity for wideband code-division multiple access (WCDMA) applications. Measurement results with the continuous wave (CW) signals indicate that the designed class-F PA achieves a peak power-added efficiency (PAE) of 75.2% with an output power of 39.4 dBm. The adjacent channel power ratio (ACPR) of the designed PA after digital predistortion (DPD) decreases from −28.3 and −27.5 dBc to −51.9 and −54.0 dBc, respectively, for a 4-carrier 20 MHz WCDMA signal with 7.1 dB peak to average power ratio (PAPR). The drain efficiency (DE) of the PA is 37.8% at an average output power of 33.3 dBm. The designed power amplifier can be applied in the WCDMA system.

Key words: digital predistortion; peak power-added efficiency; drain efficiency; adjacent channel power ratio; efficiency; linearity; class-F power amplifier

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The RF power amplifier tends to be the most power-hungry block for a typical transmitter system, leading to a stringent requirement for efficiency. It is a challenge to maintain high efficiency during operation over the wide instantaneous power range for modern modulation signals such as WCDMA and LTE, while meeting their demanding linearity requirements [1−2].

Switching mode PAs, such as class-E, class-F and inverse class-F[3−5] have been demonstrated to improve the efficiency, but they have the problem of poor linearity caused by the bias at cut-off, leading to severe out-of-band interference and in-band distortion. To avoid the nonlinear distortions caused by the PAs, digital predistortion (DPD) is considered as the most cost effective method among all the linearization techniques.

In the past few years, many behavioral models have been proposed to characterize the nonlinear and memory effects of the PA[6−9]. Among these models, the Volterra series model was considered as a general way to model a nonlinear system with memory, but with a high computational complexity. The dynamic deviation reduction-based Volterra series model proposed in Refs. [10 − 11] and the simplified visions[12−13] that followed not only significantly reduced the complexity of the Volterra series model, but also made the model parameters extraction more flexible.

In this paper, a class-F switch mode PA along with the DPD based on the simplified second-order dynamic deviation reduction-based Volterra series model[12−13] is used to optimize the PA's intrinsic efficiency-linearity trade-off. The experimental results show that the designed digital predistorted class-F PA obtains high drain efficiency and excellent linearity for the 4-carrier WCDMA signals at an average output power of 33.3 dBm.

1 Class-F Power Amplifier Design

Ideally, the class-F PA must have all of the odd harmonics terminated with an open circuit at the intrinsic drain of the transistor to generate the squared voltage waveform and all the even harmonics with a short circuit termination for the harmonic current. However, it is not practical in the real design. In this paper, only the second and the third harmonic load impedances are considered. The topology of the circuit is shown in Fig. 1.

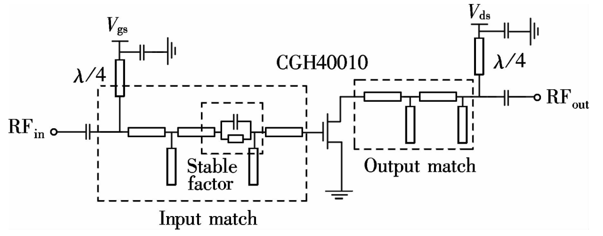

Fig. 1 Circuit topology of the class-F PA

1.1 Circuit topology

The second and the third harmonic load impedances are implemented in the output match network. The input match network provides proper harmonic impedance at the transistor's gate to improve efficiency. A resistor serially connected on the input end is used to improve the stability

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of the circuit.

1.2 Implementation and measurement results

Fig. 2 shows the picture of the final designed class-F PA based on the circuit parameters in Fig. 1.

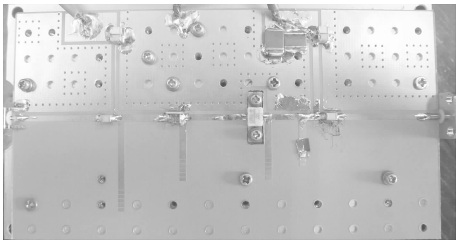

Fig. 2 Photograph of the designed class-F PA

With the gate voltage biased at −2.8 V and the drain voltage biased at 28 V, the measured PAE, the output power and the gain with the input power of 25 dBm for the frequency swept from 2.07 to 2.17 GHz are plotted in Fig. 3. The PAE is greater than 60% and the output power is greater than 38 dBm in the range of 2.07 to 2.14 GHz. Fig. 4 presents the measured PAE, the output power and the gain at 2.12 GHz for the input CW signal power swept from 8 to 28 dBm. A peak PAE of 75.2% is obtained with a maximum output power of 39.4 dBm.

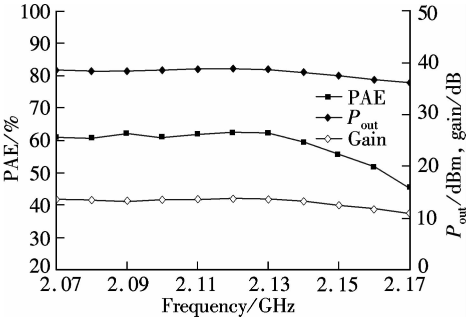

Fig. 3 Measured PAE, gain and P_{out} vs. input frequency with input power of 25 dBm

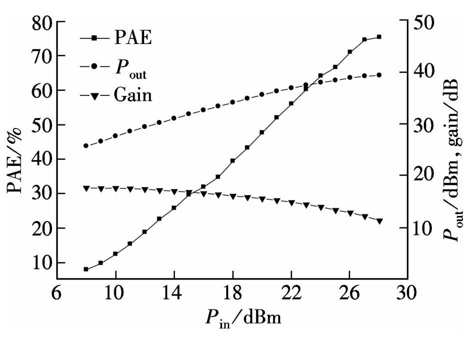

Fig. 4 Measured PAE, gain and P_{out} vs. input power at 2.12 GHz

2 Digital Predistortion Experimental Results

The experimental platform set up similar to that in Refs. [5, 14] is used to validate the linearity improvement of the designed class-F PA (see Fig. 5). A vector signal generator (Rohde & Schwarz SMBV100A), a vector signal analyzer (Agilent N9030A), a PC with Matlab and Agilent's 89600 vector signal analyzer (VSA) software, and the class-F PA under test constitute the open-loop DPD validation system. All the instruments and the PC are connected in a local area network (LAN), where the data can be downloaded from the Matlab to the vector signal generator and the collected data in the vector signal analyzer can be transferred to the PC by the LAN cable.

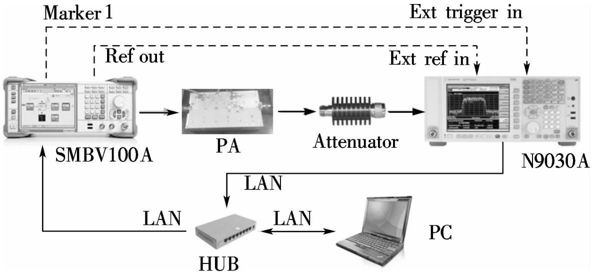

Fig. 5 Experimental validation platform

The class-F PA is operated at 2.12 GHz and excited by a 4-carrier WCDMA signal with 7.1 dB PAPR. A total of 3 556 I/Q samples with an oversample factor of 4 are generated in the Matlab and downloaded to the vector signal generator with a sample rate of 80×10^6 sample/s, yielding the 20 MHz signal. The baseband I/Q signals are modulated and up-converted to 2.12 GHz in SMBV100A, and then amplified by the class-F PA. After appropriate attenuation, the output distorted signal of the PA is down-converted and demodulated by N9030A. A total of 7 112 I/Q samples are captured at the output of the PA with an I/Q sample rate of 80×10^6 sample/s. After time alignment and normalization, 3 556 samples are used for model parameter extraction.

In order to accurately model the nonlinearity and memory effects, the nonlinearity order in the Volterra model is set to be 9, while the memory depth is set to be 7. Comparisons of the experimental results at different average output powers are shown in Fig. 6. After DPD, the linearization results in terms with ACPR below −50 dBc are obtained at an average output power of no greater than 33.3 dBm.

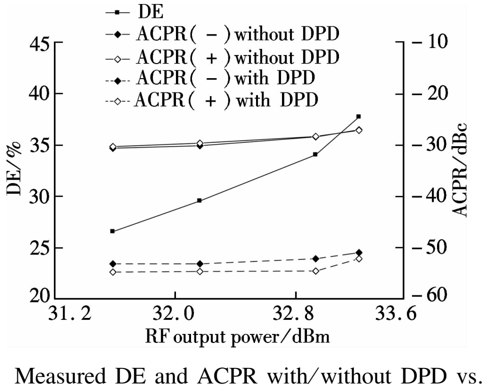

Fig. 6 Measured DE and ACPR with/without DPD vs. average output power level

Fig. 7 presents the measured power spectral density (PSD) of the PA with and without DPD at an average output power of 33. 3 dBm. The measured ACPR are decreased to −51. 9 dBc (lower) and −54. 0 dBc (upper) from −28. 3 dBc (lower) and −27. 5 dBc (upper), respectively, with a drain efficiency of 37. 8%.

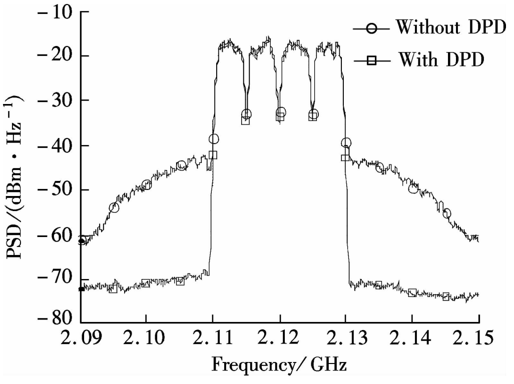

Fig. 7 Measured PSD of the PA output with/without DPD at average output power of 33. 3 dBm with drain efficiency of 37. 8%

The linearized class-F PA reported in this paper with 20 MHz 4-carrier WCDMA signals is compared with a selection of comparable state-of-the-art linearized switching mode PAs as shown in Tab. 1.

Tab. 1 Linearized switching mode PA comparison

Mode	PA	Signal bandwith/MHz	DE/%	P_{out}/dBm	Frequency/GHz
Ref. [4]	Class-E	10	45	33. 5	2. 1
Ref. [5]	Class-F^{-1}	20	31. 3	33. 6	2. 55
Ref. [15]	Class-F^{-1}	10	27. 9	29. 8	3. 3
This paper	Class-F	20	37. 8	33. 3	2. 12

3 Conclusion

In this paper, a class-F power amplifier using Cree GaN HEMT CGH40010 operating at 2. 12 GHz is implemented for WCDMA applications. The designed class-F PA achieves a PAE of 75. 2% with an output power of 39. 4 dBm. For the 20 MHz 4-carrier WCDMA signals, the ACPR is decreased to be −51. 9 and −54. 0 dBc by using the DPD technique with a drain efficiency of 37. 8% at an average output power of 33. 3 dBm.

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应用于 WCDMA 的高效率 F 类功率放大器及数字预失真

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摘要：采用 Cree 公司的 GaN 晶体管 CGH40010，设计了一个工作在 2.12 GHz，用于 WCDMA 的带有数字预失真的高效率 F 类功率放大器，以实现其高效率和高线性度. 经过连续波信号测试，设计完成的 F 类功率放大器实现了 75.2% 的功率附加效率和 39.4 dBm 的最大输出功率. 对峰均比为 7.1 dB、带宽为 20 MHz 的 4 载波 WCDMA 信号，经过数字预失真线性化技术后，F 类功放在 33.3 dBm 的平均输出功率下，输出信号的邻信道功率比分别由 −28.3 和 −27.5 dBc 降低到 −51.9 和 −54.0 dBc. 功放的漏极效率达到 37.8%. 所设计的功率放大器可用于 WCDMA 系统中.

关键词：数字预失真；功率附加效率；漏极效率；邻信道功率比；效率；线性度；F 类功放

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