

High Efficiency Power Transmitter Based on Envelope Delta-Sigma Modulation (EDSM)

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Abstract—A Delta-Sigma modulated Class-E power amplifier is proposed and experimentally developed for high-efficiency and linear applications. The essential idea is based on the Envelope Delta-Sigma Modulation (EDSM), which combines the Kahn technique Envelope Elimination and Restoration (EER) and the Delta-Sigma modulated amplifier concept. The EDSM scheme increases the efficiency of the circuit by digitalizing the envelope of the signal instead of the original RF signal. In the proposed scheme, the digitized envelope is not filtered as in the Kahn Technique; consequently the output signal linearity is not deteriorated by the amplifier nonlinearity. A band pass filter is used only at the output of the system after the Class-E power amplifier to restore the original signal envelope.

Keywords—component; Class E, delta-sigma, high efficiency, linearity, modulation, power amplifier.

I. INTRODUCTION

In modern wireless communication systems, highly efficient circuits are required to transmit and receive data with less consumption of DC power in order to preserve the lifetime of the battery and to reduce the size of the heat sink of the transistors. In addition, most of the communication formats utilize non-constant envelope to carry more information within limited spectrum. This necessitates highly linear power amplifiers for high fidelity data transmission.

Many of high power efficiency amplifications schemes, however, compromise the signal linearity. Typical examples include those called switched mode amplifiers (Class D, E, F, S). These amplifiers are able to amplify single-tone signal efficiently but will generate intermodulation distortions for envelope sensitive signals.

The Kahn technique was introduced in the 1950s to improve efficiency, also known as Envelope Elimination Restoration (EER). In this method the input signal is split into two branches: one carries the envelope the other retains only the phase information [1, 2]. In one branch, the envelope is digitized through a pulse width modulator, then it is amplified with a Class-S amplifier and finally it is filtered through a low pass filter. The other branch carries the phase information. The envelope is restored to the carrier through controlling the drain bias of the RF amplifier. However, the Kahn technique assumes that the power amplifiers (PA) behave like a linear

modulator with high efficiency through the drain control, which is often not the case in practice.

A promising approach, proposed in [3, 4], digitalizes the RF signal via a delta-sigma modulator to drive the Class-S amplifier. The RF signal is recovered using a high Q band pass filter. Although this technique shows the promise of a good efficiency as well as a good intermodulation performance by way of the delta-sigma modulator, it is difficult to realize at RF frequencies since the driving digital signal speed must be at least a few times higher than the carrier frequency.

A combination of both of the previously mentioned techniques was first proposed in [5,6], called the Envelope Delta-Sigma Modulation (EDSM) technique. This technique promises a high efficiency for transmitters with low intermodulation distortion. The EDSM makes use of the EER feature of the Kahn technique to separate the signal into a carrier and an envelope. However, instead of restoring the signal envelope using the drain supply of the amplifier, the envelope is digitized and modulated back to the carrier signal. The digitally modulated signal is then directly fed into a Class-E amplifier, as the switched mode amplifier has the similar high efficiency for both constant envelope signal and signal with digitized envelope. Compared to the direct Delta-Sigma sampling idea [3, 4], only the envelope signal is digitized in the EDSM scheme, which makes the proposed approach feasible for RF applications even with the existing semiconductor device technology.

In this paper, the EDSM scheme is realized experimentally based on a Class-E power amplifier at 2.47 GHz. A band pass filter has been placed at the output of the Class-E power amplifier to suppress the sampling noise outside the frequency band and to restore the linearity. The measured results show that a drain efficiency of 43% and a power added efficiency (PAE) of 32% for a 3-tone signal have been achieved even with a band pass filter of 2 dB loss.

This paper is organized as follows. Section II describes the principles of the proposed EDSM amplifier. Section III shows the measured results of a Class-E power amplifier. Section IV presents the experimental realization and performance of a preliminary EDSM system.

II. SYSTEM ARCHITECTURE

The EDSM presented in this paper is shown in Fig. 1. The input RF signal is split into two branches an envelope and a carrier. The envelope is digitized by a Δ - Σ modulator in the upper branch and modulated on the carrier extracted by a limiter in the lower branch. The modulator restores the digitized envelope to the phase-modulated carrier. A detailed spectrum analysis can show that the carrier signal modulated by the digitized envelope will not introduce in-band distortion while passing through a switching mode amplifier. This is further validated by the experimental results shown in chapter IV. The power efficiency achieved for this type of waveform also approaches a constant-envelope signal. The band pass filter at the output restores the original modulated signal. The quantization error of the delta-sigma modulator will generate intermodulation among different tones for envelope sensitive signals. However, as the delta-sigma modulator has an interesting noise shaping property; most of the quantization error will behave like noise outside the interested frequency band in spectrum domain. This noise can be easily filtered out thanks to the feed back loop used to automatically eliminate the quantization errors at low frequencies, which also assures the reliable restoration of the original signal envelope. The EDSM provides the advantages of high power efficiency in amplification and the linearity of the output signal is up to the precision of the delta-sigma modulation and is not anymore affected by the power amplifier itself.

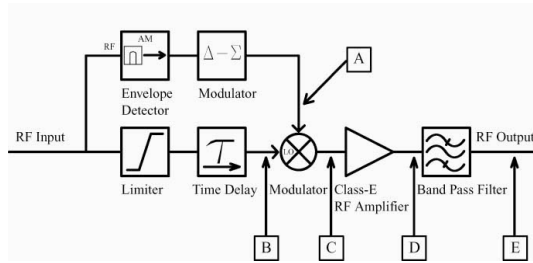


Figure 1. Block diagram of the improved Kahn technique transmitter.

III. CLASS-E POWER AMPLIFIER

A Class-E power amplifier was chosen because of its ability to operate in switching mode that enables high efficiency. The drain-voltage drops to zero when the switch is on-state and the drain-current waveforms is maximum. In the off-state, the current is zero and the voltage is high. In this way the power consumption is minimized, therefore ideally an efficiency of 100% can be obtained. [7, 8]. The transistor chosen to realize this Class-E PA was the MwT-8 at 2.47GHz. The substrate used is the RT/Duroid 5870 with $\epsilon_r=2.33$ and $h=31$ mil. The bias voltages chosen are $V_{ds}=4.3V$ and $V_{gs}=-3.03V$, after tuning. Fig. 2 shows the power added efficiency (PAE) and drain efficiency (η) with respect to the input power.

The power added efficiency (PAE) is defined as:

$$PAE = \frac{P_{out} - P_{in}}{P_{dc}}, \quad (1)$$

where P_{out} is the output power in watt, P_{in} is the input power in watt and P_{dc} is the power consumption in watt.

The drain efficiency (η) is:

$$\eta = \frac{P_{out}}{P_{dc}} \quad (2)$$

The simulations were performed with Agilent ADS using the model of the MwT-8 provided in the library. The maximum PAE obtained is 64% and the maximum drain efficiency (η) is 70% at 2.47 GHz with 20 dBm (100 mW) of output power and a gain of 10.83 dB. Those maxima are obtained for an input power of 9.5 dBm (8.91 mW).

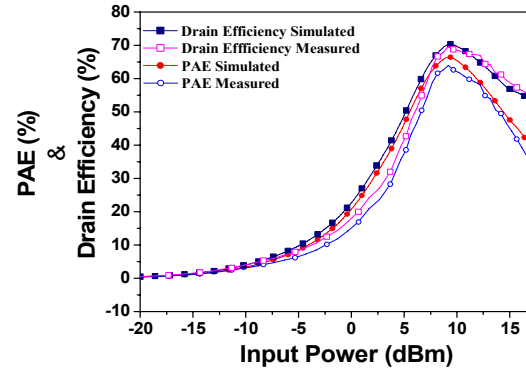


Figure 2. Power-added efficiency (simulated, measured) and drain efficiency (simulated and measured) versus input power for the 2.47 GHz MwT-8.

IV. THE ENVELOPE DELTA-SIGMA MODULATION (EDSM)

A. Class-E power amplifier with a band pass filter

As it was described in section II, in order to recover the analog signal a band pass filter is inserted at the output of the PA. Fig. 3 is the picture of the Class-E with the band pass filter integrated.

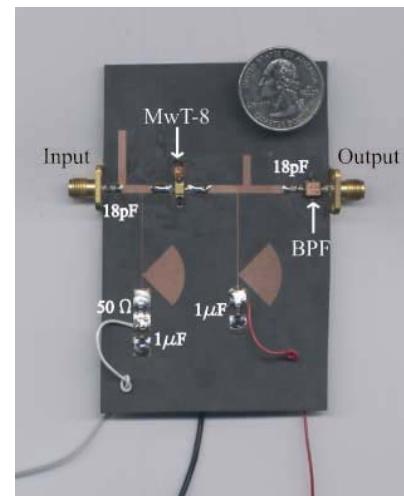


Figure 3. Photograph of the Class-E PA with the band pass filter

The band pass filter (BPF) employed is the Murata DFCB22BG48LBJAA with a bandwidth of 26 MHz, and an insertion loss of 2dB. Fig. 4 shows the measured power-added efficiency and drain efficiency versus input power at 2.47GHz for the Class-E PA followed by the BPF. The output power decreases by 2dBm due to the insertion loss of the filter. A maximum PAE and drain efficiency were observed on Fig. 2 for an input power of 9.5 dBm (8.91 mW) and an output power of 20dBm (100 mW). On Fig. 4 for the same input power of 9.5 dBm, the output power is now 18 dBm (63.1 mW). That is due to the 2dB losses introduced by the band pass filter. The maximum drain efficiency is now 44% and the maximum PAE is now 38%.

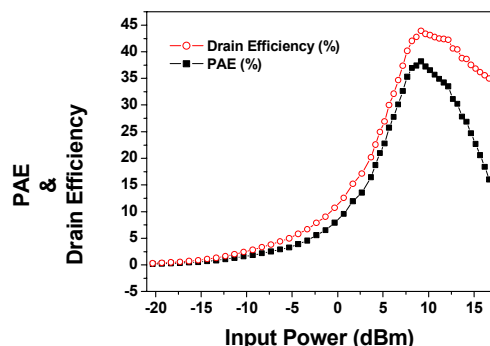


Figure 4. Power-added efficiency and drain efficiency versus input power at 2.47GHz for the Class-E PA followed by the BPF (with a 2 dB insertion loss) shown on Fig. 3 for a single tone measurement.

B. Measured Results of the Envelope Delta-Sigma Modulation (EDSM)

The transmitter concept was verified using a combination of software and hardware measurements. The input signal is a 1 MHz sinusoid envelope signal modulating on a 2.47GHz carrier. The modulation index is 50% to allow continuous phase in the carrier. In spectrum it consists of three tones at 2.47GHz and 2.47GHz \pm 1MHz. To avoid the fabrication of a real-time Delta-Sigma modulator, the envelope signal was first processed using delta-sigma modulator programmed in Agilent Advanced Design System (ADS) software to find the output. A second-order delta-sigma modulator with 200MHz clock frequency is used to sample the signal. The delta-sigma envelope was then programmed into an arbitrary waveform generator, Sony Tektronix AWG520, which generates the digitized envelope. The digitized envelope is then modulated on the RF carrier in the experiment.

In Fig. 1 the digitized delta-sigma envelope is applied at point A and the phase is applied at point B. The phase is modulated to the delta-sigma envelope then this modulated signal goes to the input of the Class-E power amplifier at point C. Finally the output of the PA is filtered through the Band Pass Filter (BPF) at point D. On Fig. 5 are plotted the measured PAE and the measured drain efficiency versus the input power in dBm, for a three tones input signal. As the band pass filter Murata has a 2dB insertion loss. For the corrected Drain Efficiency and PAE corrected curves, 2dBm were added to the output power to de-embed the insertion loss of the filter. It can be noticed that the linearity of the system has been improved.

The drain efficiency with the EDSM is almost constant and equal to 43% for an input power varying from 7.7 dBm to 17.7 dBm. If the loss of the band pass filter is de-embedded the drain efficiency is now constant and equal to 69.5% (Drain Efficiency corrected on Fig. 5) for an input power varying from 7.7 dBm to 17.7 dBm. The same observation can be made for the PAE. The maximum PAE reached is 32%, and the corrected PAE is 57.2% (with the 2dB loss of the band pass filter de-embedded).

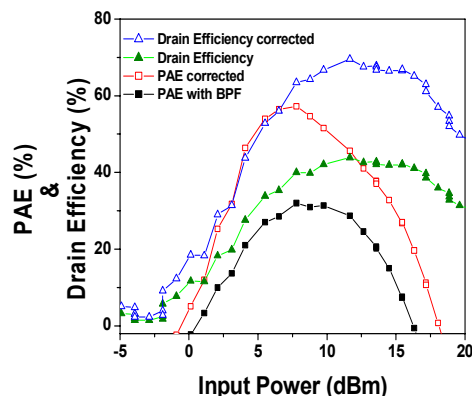


Figure 5. Power-added efficiency and drain efficiency versus input power at 2.47GHz for the IKT measurement. (Drain efficiency corrected and PAE corrected: the 2dB insertion losses of the BPF were subtracted from the output power.

C. Intermodulation

Fig. 6 is the simulated spectrum of the delta-sigma modulator output generated with ADS, with a third order intermodulation (IM3) level of 21.3 dBc. The IM3 is defined as the ratio between the upper-side-band envelope spectrum and the first intermodulation term besides. A delta-sigma envelope was generated with ADS in order to program the arbitrary waveform generator. In this way it was possible to be close to the simulations achieved. Fig. 7 is the measured spectrum of the input power at the input of the PA with a span of 5 MHz, and IM3 level of 15.66 dBc.

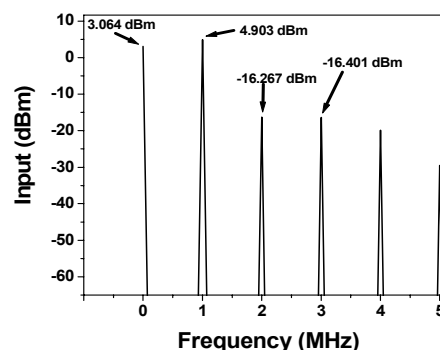


Figure 6. Simulated spectrum of the delta-sigma modulator with ADS

This indicates a non-perfect delta-sigma modulation during the process of the arbitrary waveform generation and the amplitude modulation. Fig. 8 is the measured spectrum of the output power of the EDSM with a span of 5MHz and IM3 level of 18 dBc. The IM3 performance does not reduce but actually

improves from 15.66 dBc to 18 dBc after amplification. This may be due to the rounding effect of the amplifier device for high speed modulation. The measured intermodulation terms fall in the pass band of the filter and the quantization noise shaped outside the band is suppressed by the band pass filter.

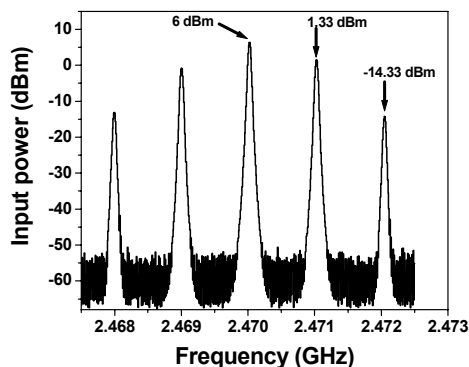


Figure 7. Measured spectrum of the input power measured at the input of the PA with a span of 5 MHz

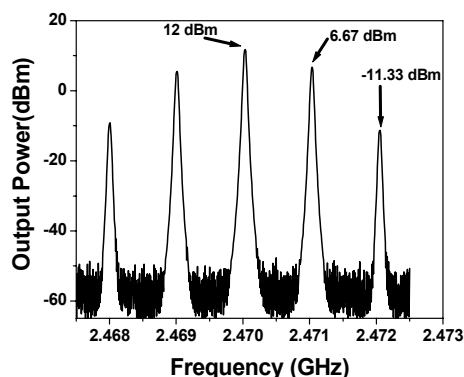


Figure 8. Measured spectrum of the output power of the EDSM measured with a span of 5 MHz.

V. CONCLUSION

A novel transmitter architecture is proposed for both high efficiency and high linearity applications. The essence is to implement envelope delta-sigma modulator on top of switched mode amplifiers. Experimental results have shown that the system provides high power efficiency for non-constant-envelope signals while maintaining the linearity performance. In order to fully explore the potential of this approach, a low loss band pass filter is needed at the output, which poses new challenges to the filter design.

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