Linearized Switching Amplifier

R. Mahmoudi, D. Milosevic, J.D. van der Tang, J. A. Hegt and A. H. M. van Roermund

Eindhoven University of Technology, Electrical Engineering, Mixed-signal Microelectronics Group, Den Dolech 2, Building EH 5.26, 5600 MB, Eindhoven, The Netherlands, + 31 40 247 3192

***Abstract* — Two different concepts for high efficiency linear amplification of variable envelope RF signals are presented. The EER concept is based on a Class-E PA, and it has been demonstrated that excellent ACPR performance can be achieved. The Class-E PA employs a GaAs HBT device and the simulated PAE is higher than 70% at 2 GHz. The wideband linearization feature of the "Limit Duty Cycle Modulation" technique, in conjunction with the applicability of the switching type amplifiers enables the realization of a new kind of transmitter architecture that facilitates the optimization of linearity and power-efficiency. A suitable limit duty cycle configuration for broadband communication applications is introduced and considered in some depth.**

I. INTRODUCTION

The exponential growth of the mobile and wireless applications is continuing unabated so that more and more demands are being placed on the available spectrum. This has in turn stimulated deployment of complex modulation techniques such as QAM as well as spread spectrum system. Preserving the required severe linearity constraints using the conventional methods, however, deteriorates the overall power efficiency [8]. Reconciliation of the power-added efficiency and the spectral bandwidth efficiency has been addressed by different methods using the switching type amplifiers e.g. the Envelope Elimination and Restoration (EER) technique and the Limit Duty Cycle principle (see [1], [3] and [5]). In this paper, we will discuss the applicability of Class-E power amplifiers for non-constant envelope RF signals as well as the potential of the Limit Duty Cycle modulation technique for broadband communication systems.

II. CLASS-E PA AND EER

The Class-E was introduced in 1975 by Sokals [1] and since then a lot of research has been done on this interesting type of circuit. It brought a unique feature of "soft switching" into the family of switching type power amplifiers, thus theoretically enabling unprecedented efficiencies to be achieved, even at frequencies in the GHz range.

A basic, single-ended Class-E circuit in its original form is depicted in figure 1. The circuit consists of an active device, an RF choke and surrounding passive elements that form the load network. The transistor is operated as a switch: in the ON state, it is heavily overdriven by the input signal, and in the OFF state it is in non-conductive (cut-off) state. Due to the carefully arranged transient response of the load network, there is no overlap of significant collector voltage and current values and high efficiency operation can be achieved.

We have designed and simulated a Class-E PA circuit for operation at 1.9 GHz and output power level of approximately 24 dBm (250 mW). The circuit is based on a GaAs heterojunction bipolar transistor (HBT) in a typical commercially available process with f_T=30 GHz. Figure 2 displays the simulated collector current and voltage waveforms that approximate the ideal Class-E operation relatively well. The PA is supplied by 3V DC, taking care not to exceed the breakdown limitation of the HBT device (BV_{CEO}=12V). A standard 50-Ohm signal generator with P_{in}=9dBm of drive power is used, in addition to a carefully chosen DC offset, in order to provide a 50% duty cycle operation. Although a pure sine-wave drive does not provide optimal operating conditions for the Class-E configuration, simulations show that power added efficiency (PAE) higher than 70% can be achieved. Losses in passive components of the matching networks are taken into account and the simulated transducer power gain is higher than 15 dB.

Being a switching type PA, Class-E is inherently incapable of amplifying amplitude modulated signals. The amplitude of the output signal is essentially determined by the supply voltage and the load network elements, and the input signal is seen only as information for triggering of the active device. Therefore, any information contained in the amplitude of the input signal will be lost at the output. However, there are ways to make use of the Class-E PA for amplification of variable envelope signals. Ideally, amplitudes of all voltages in the load network are proportional to the supply voltage.

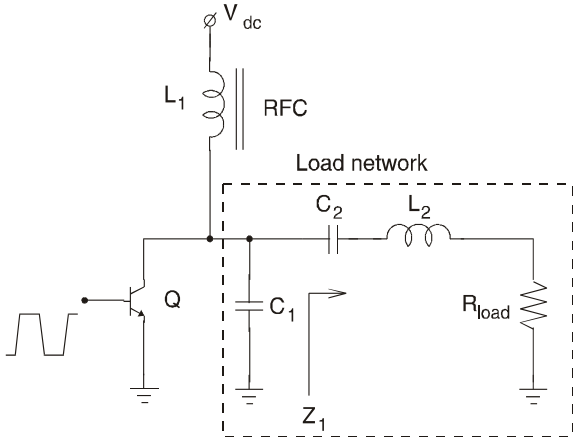

Fig 1. Class-E PA circuit.

Therefore, by changing the supply voltage it is possible to control amplitude of the output voltage. This feature presents a basic principle of the Envelope Elimination and Restoration (EER) technique. The EER concept is illustrated in figure 3.

The input RF signal, which has a variable envelope, is split into two paths. In the upper branch, the envelope of the input signal is detected and used as a modulation signal for the supply voltage of the Class-E PA. In the lower path, the input RF is passed through a limiter, thereby producing a constant-envelope phase-modulated signal with identical zero crossings as the original signal. This signal is fed to the input of the PA which recombines the envelope and phase-modulated signal and a truthful amplified replica is obtained at the output.

While the EER looks as a perfect concept, a practical implementation will face a number of difficulties. The two main problems associated with this technique are increased bandwidth requirements in both the amplitude and phase path and a differential delay between signals in these two paths. Neglecting these problems, we have designed and simulated a simplistic EER testbench similar to the concept in figure 3, in which all blocks are considered to be ideal, except for the Class-E PA circuit which is based on the model of a realistic HBT device. A Wideband Code Division Multiple Access (WCDMA) signal at 1.95GHz has been used for evaluation of the EER testbench. In figure 4, the original and amplified WCDMA RF signals are shown. Visual inspection indicates that the original variable envelope is almost perfectly restored in the output signal. In figure 5, power spectrum of the output signal is displayed.

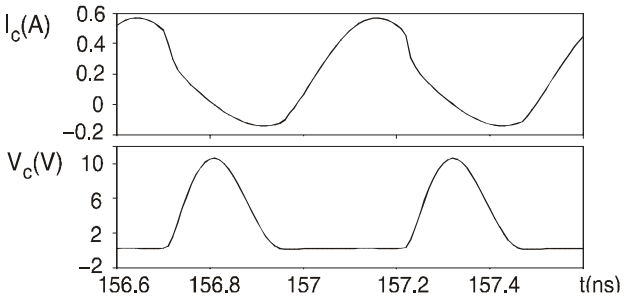

Fig 2. Simulated waveforms in the circuit.

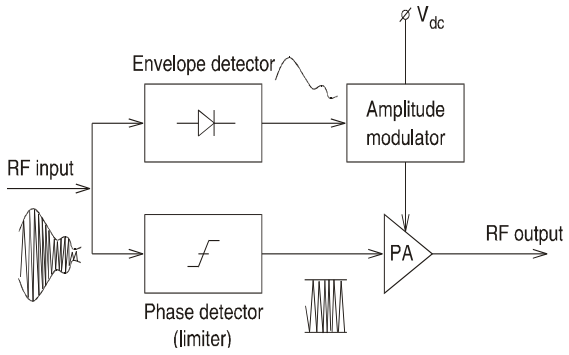

Fig 3. Block diagram of the EER concept.

The simulated Adjacent Channel Power Ratio (ACPR) performance is 34 dB and 53 dB for the first and second adjacent channel, respectively. These results satisfy the ACPR requirements of the UMTS technical specification, but other linearity measurements (e.g. EVM) may also be necessary. The presented simulation results show that Class-E power amplifiers have potential for high-efficiency linear amplification of dynamically varying RF signals, such as WCDMA. The well-known EER concept proves to be an old but attractive transmitter technique that is worth further investigation.

The simulated PAE and ACPR performance show that further research in this direction is of high importance. Effects of various imperfections, such as differential delay between the two paths, bandwidth restrictions and phase distortion of the PA etc. need to be studied in detail. An efficient implementation of the supply modulator with sufficient bandwidth and high linearity is a challenge and of crucial importance for the overall performance of the system.

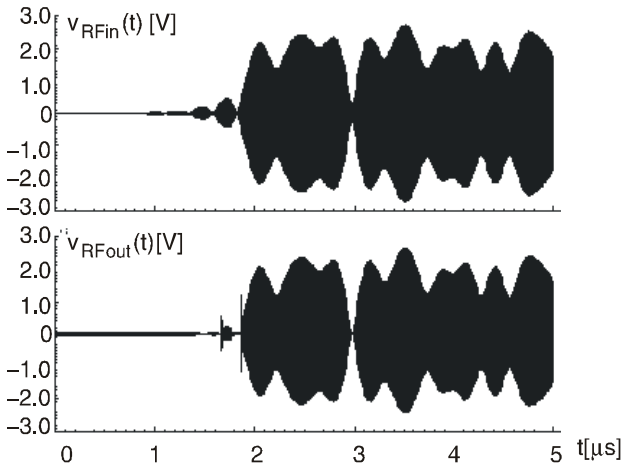

Fig 4. The original and output WCDMA RF signal.

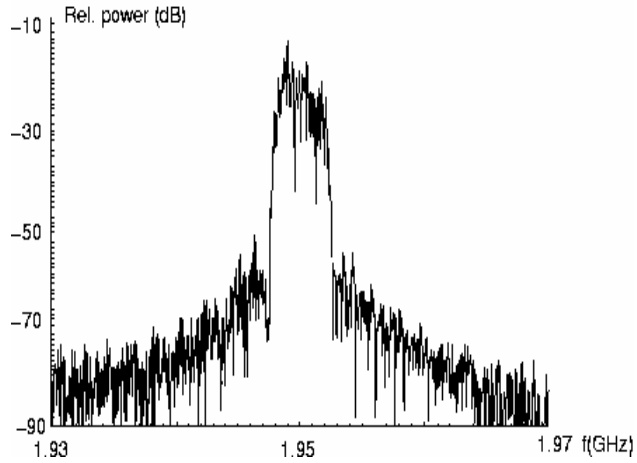

Fig 5. Spectrum of the output WCDMA signal.

III. Limit Duty Cycle Principle

A limit duty cycle modulator is a self-oscillating circuit (an initial condition-independent) consisting of a nonlinear component and a linear component which are operating in a negative feedback loop (see Fig 5). The limit duty cycle system may contain only a discreet set of limit cycle amplitudes and frequencies. The negatively back-coupled non-linear or relay device converts an input signal into a discrete-level output signal. This configuration has been referred in the literature as asynchronous sigma delta due to its pulse width modulation characteristic (see [2] and [3]). This property allows the implementation of switching type devices (e.g. a high efficiency Class S power amplifier, see [6]).

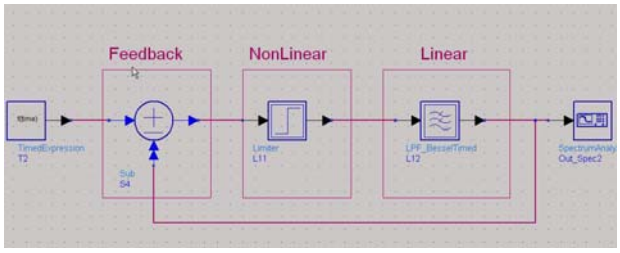

Fig 5. The basic configuration of the limit duty cycle principle.

In the absence of the input signal, the undamped oscillation frequency (the natural stability condition) of the limit duty cycle can be derived from the following equations.

$$1 + N(A,\omega)L(j\omega) = 0$$
$$\Re(N(A,\omega))\Re(L(j\omega)) - \Im(N(A,\omega))\Im(L(j\omega)) = -1$$
$$\Re(N(A,\omega))\Im(L(j\omega)) + \Im(N(A,\omega))\Re(L(j\omega)) = 0$$

N(A,ω) and L(jω) are respectively the describing function of the nonlinear component and frequency response function of the linear component. From the above equations can be concluded that when the nonlinear component doesn't possess hysteresis property, the resonation frequency of the limit cycle modulator will be determined only by the linear component.

Due to the self-oscillating properties of the limit Duty Cycle modulator, the RF input signal is modulated in such a manner that non-linear products, created by the relay device, are frequency modulated. The interference rate between the non-linear frequency modulation products and the desired frequency is on the one hand a function of the offset between the desired and the resonation frequency and on the other hand the signal's power level. This interference rate can be inclined by shifting the system's resonation frequency towards the higher frequency range which in return complicates the operational condition and deteriorates the performance of semiconductor devices.

Furthermore, improving the overall power efficiency imposes the reduction of the power consumption of the system's resonation frequency which can be achieved either by the increasing the impedance level at the resonation frequency or by suppressing the power level of the system's resonation frequency.

IV. Limit Duty Cycle Modulator

The wideband linearization feature of the "Limit Duty Cycle Modulation" technique, in conjunction with the applicability of the switching type amplifier (see [6] and [7]) enables the realization of a new kind of transmitter architecture that facilitates the optimization of linearity and power-efficiency. Fig 6 presents a limit duty cycle modulator which comprises a comparator, a switching type amplifier and two linear elements. The primary linear element is considered to be the required Class S matching network while the auxiliary filter is supposed to regulate the system's resonation frequency. In the absence of the auxiliary filter the primary linear element has to:

- determine the resonation frequency,
- act as the output termination,
- suppress the magnitude of the oscillating frequency.

The imposed restrictions on the characteristic of the primary linear component complicate the design process of the filter. An additional degree of freedom can be introduced by an auxiliary filter in the feedback path. In this way, the primary filter can regulate the output termination and simultaneously restrict the power dissipation of the resonation frequency, while the auxiliary filter adjusts the resonation frequency.

V. Simulation Results

For illustrative purposes, the primary filter is assumed to be a Bessel type filter and the resonation frequency of the system is normalized to one. Figure 7 and Figure 8 present the signal to noise and distortion ratio, SNDR, as a function of the input power level. The desired signal is allocated at the 1/5 of the resonation frequency and the SNDR is measured in a bandwidth of 2/5 of the resonation frequency.

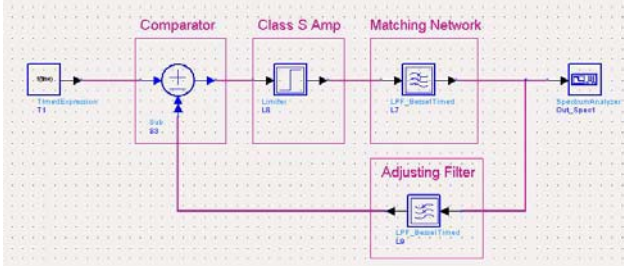

Fig. 6. The Limit Duty Cycle configuration suitable for broadband communication applications.

Figure 9 presents the response of the system to a QAM-16 which has a bandwidth of 1/8 of the resonation frequency and is allocated at the 1/5 of the resonation frequency.

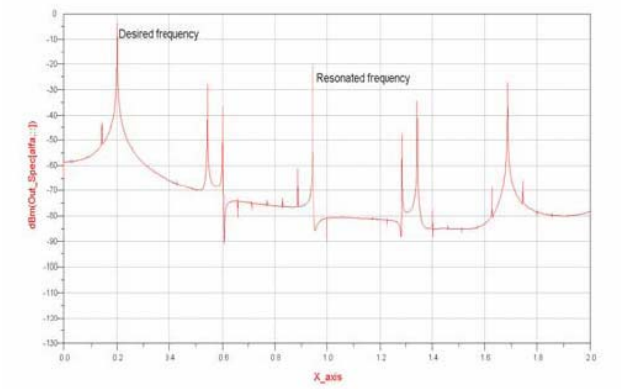

Fig. 7. The desired frequency and the suppressed resonation frequency at the output of the purposed Limit duty cycle configuration.

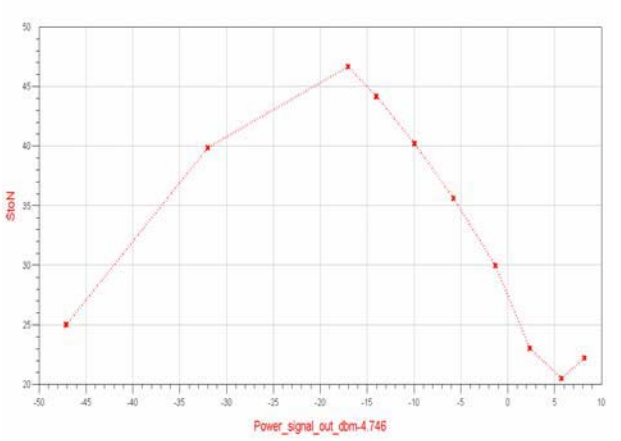

Fig. 8. The signal to noise and distortion ratio.

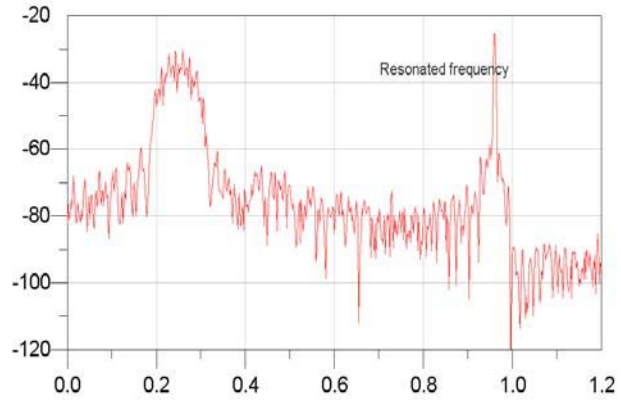

Fig. 9. The response of the limit duty cycle modulator to a QAM-16.

VI. Conclusion

Two different concepts of achieving high-efficiency linear amplification of non-constant envelope RF signals have been presented. The EER is a relatively old but attractive transmitter technique and can make use of highly efficient Class-E power amplifiers. The simulation results show that the Class-E PA, although inherently extremely non-linear, can satisfy ACPR requirements in even such a demanding system as WCDMA, provided that appropriate signals are fed to the PA circuit. A practical implementation of the EER principle contains a number of challenges and further research in that direction is of high importance.

The wideband linearization feature of the "Limit Duty Cycle Modulation" technique, in conjunction with the applicability of the Class S power amplifier, enables the realization of a new kind of transmitter architecture that facilitates the optimization of linearity and power-efficiency over a large operating-range of output power level and frequency bandwidth. Distinguished characteristics of the presented configuration enable the achievement of an optimal linearization amplifier in terms of linearity, efficiency, bandwidth and dynamic range.

Acknowledgement

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