Burst Mode Operation as an Efficiency Enhancement Technique for RF power amplifiers

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Abstract

In this paper, the Burst Mode operation is proposed as an efficiency enhancement technique for RF power amplifiers. The essence of the burst mode operation is to modulate the amplitude of the envelope signal into a series of pulses such that the width of the signal burst or the total amount of pulses are varied according to the envelope. The phase information is still contained by the timing of the pulses. This work presents an introduction of the burst mode operation and the efficiency of Burst Mode RF power amplifiers is briefly analyzed. The improvement on the efficiency with a wideband load and a narrow band filter are both illustrated. To demonstrate the validity of the proposed Burst Mode operation, a PCB-mounted Burst Mode PA using a LDMOS transistor has been fabricated. Measurements show a peak efficiency of 78% and 28.5dBm output power and an efficiency of 49.5% at 6dB power back-off.

1 Introduction

The most important challenge for today's RF PA designer is to design a power amplifier that provides the required linearity necessary for the future mobile communication standards, e.g. LTE, without sacrificing efficiency [1]. In addition, the RF PA in a mobile phone handset should be designed to deliver significant output power to the load and thus maximize the efficiency to conserve the battery power. However, linear power amplifiers only achieve high efficiency when operating near their peak output power level and have very low efficiency at power back-off. As a consequence, this will result in a reduction of battery lifetime for the portable wireless high-end user devices, certainly when the envelope of the signal is such that it rarely reaches the peak amplitude [2].

To improve the efficiency performance of the power amplifier, switching amplifiers are very attractive candidates because of their potential to obtain high efficiency – ideally 100% for the Class E if the transistor is considered as an ideal switch [3]. Now one should encode the amplitude information of the modulated signal into the time domain such that the amplitude of the input signal is always maximal and as such that the efficiency is enhanced [4]. Not only efficiency is improving, but also linearity improves because the carrier amplitude is only a function of the amount of bursts considered in time domain, which can be accurately realized by the digital modulator in the transmitter front-end.

This paper will discuss burst mode operation in more detail in section 2 and the efficiency of the Burst Mode RF PA will be briefly analyzed. The formulas derived in this section will prove the efficiency enhancement of the burst mode RF PA compared to the conventional Class B PA. To validate the analysis, a Class E switching PA has been build on PCB material and in section 3 the simulation and measurement results are shown.

2 Burst Mode Operation

The ideal operation of the burst-mode RF PA is amplifying the RF burst, which is realized by the multiplication of the RF carrier with the pulse width modulated signal (PWM), where its duty cycle is varied depending on the amplitude information of the base band signal.

A burst-mode power amplifier has two modes of operation as illustrated in figure 1: during the 'ON'-period of the applied burst signal, the amplifier is amplifying the signal and on the contrary, during the

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‘OFF’-period no input burst is applied to the power amplifier, and hence the amplifier will be completely off. The efficiency of the amplifier is thus high in both the ‘ON’- and ‘OFF’-period. At the input of the PA, during the ‘ON’-period, a signal with constant amplitude is applied to ensure the RF power amplifier continuously operates in saturation and consequently generates the output signal with peak efficiency and amplitude, which is represented as a normalized amplitude of ’1’ in figure 1. The amplitude information of the RF signal is now reconstructed by introducing a narrow band-pass filter at the output of the amplifier [5]. Considering an ideal filter, then the signal at the output of the filter is a perfect sine wave at the carrier frequency, whose normalized amplitude is equal to the duty cycle, δ, of the burst period, T_{burst}. All this means that the amplitude at the output of the Burst Mode power amplifier with filter is linearly related with the duty cycle of the applied input burst or in other words, the amplitude information is translated into time domain and is represented by the duty cycle and the phase information is still contained by the carrier itself during the ‘ON’-period.

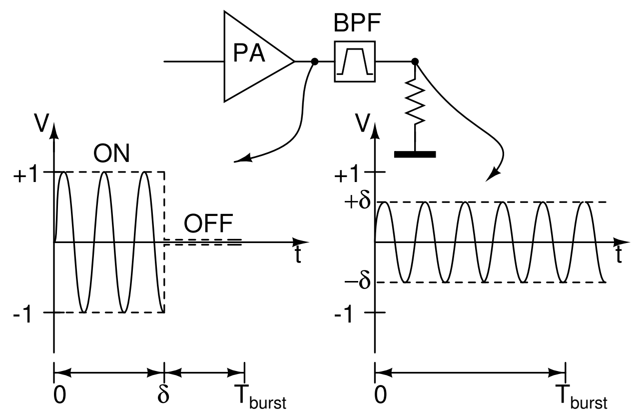


Figure 1: Block diagram of the burst mode transmitter architecture

Thus the RF bursts at the output of the Burst Mode PA contain both in-band and out-of-band spectral components and their dependency on the duty cycle is depicted in equations (1-3).

$$P_{tot} = P_{inb} + P_{outb} \quad \propto \quad \delta \tag{1}$$
$$P_{inb} \quad \propto \quad \delta^2 \tag{2}$$
$$P_{outb} \quad \propto \quad \delta\,(1-\delta) \tag{3}$$

If the Burst Mode amplifier sees a 50Ω-wideband load, the out-of-band power is dissipated and the efficiency, η_{BM_PA}, is calculated as

$$\eta_{BM\_PA} = \frac{P_{inb}}{P_{inb} + P_{outb}} = \delta \tag{4}$$

This efficiency performance is exactly the same as the conventional Class B. In a Class B, assuming that the supply voltage is kept constant, the DC power consumption of the PA scales linearly with the input signal. The output power obviously scales quadratic with the input signal amplitude and as such, the efficiency is proportional to the square root of the output power.

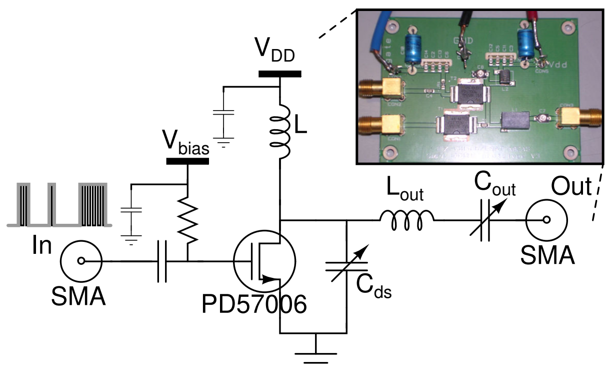
The core idea to improve the efficiency is to reduce the out-of-band signal dissipation. Adding a narrow band filter at the drain of the transistor of the switching mode PA raises the impedance seen by the transistor at the out-of-band frequency components. The ratio of the out-of-band power to the total power is now reduced and the efficiency at power back-off is increased. Ideally, no out-of-band spectral components are dissipated, hence the efficiency of the switching mode power amplifier would be maximal for every duty cycle. In this case, $P_{outb} = 0$, the efficiency of the Burst Mode power amplifier becomes

$$\eta_{BM\_PA} = \frac{P_{inb}}{P_{inb}} = \eta_{PEP} \tag{5}$$

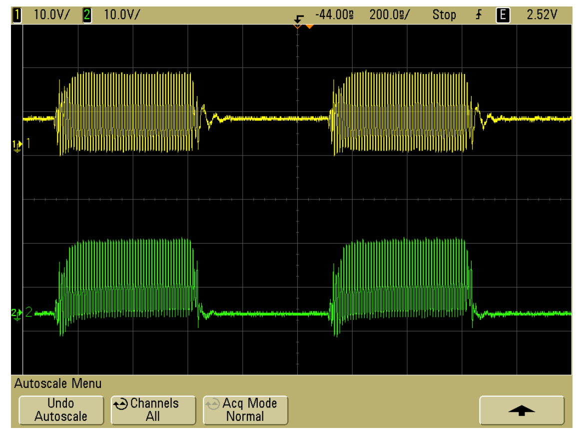
assuming that the transistors have a peak efficiency of η_{PEP}.

3 Measurement results

Since switching amplifiers have a very high peak efficiency, η_{PEP}, it is clearly beneficial to use a switch-mode amplifier in this burst mode architecture. A Class E Burst Mode RF amplifier is implemented on PCB in FR4-material with discrete components. Figure 2a shows the schematic of the Class E switching amplifier. An example of the applied square wave signals with varying duty cycle is also illustrated in the schematic. The single-ended switching amplifier itself is constructed with the LDMOS-transistor PD57006. The operating carrier frequency, f_{rf}, of the Burst Mode PA is 100 MHz. The voltage waveforms at the drain of the transistor and at the output for a 50% duty cycle input signal are captured with an oscilloscope and are illustrated at the top and at the bottom in figure 2b respectively for a 50Ω load.



(a) Schematic of the Class E Burst mode RF PA

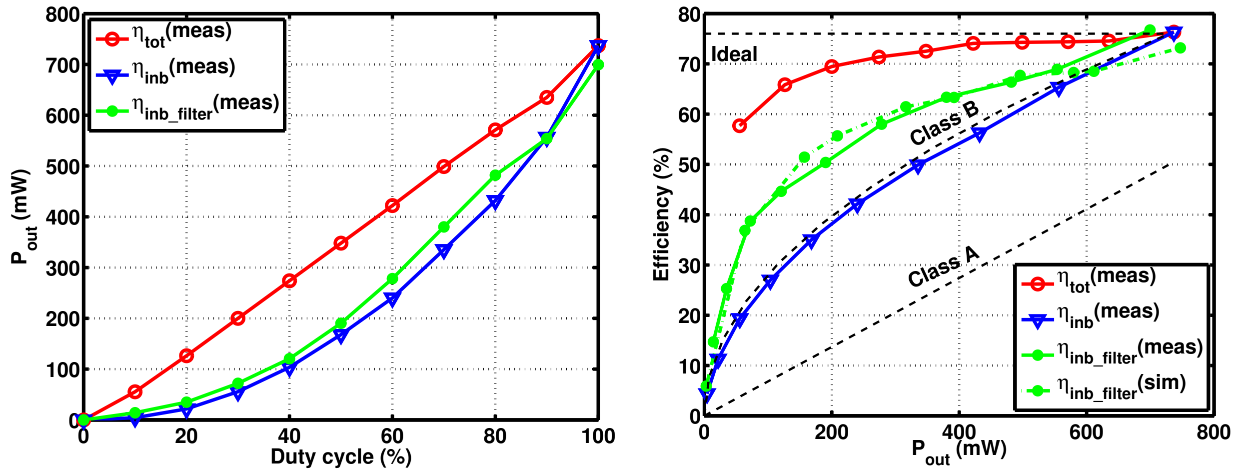


(b) Time Domain Drain Wave

Figure 2: The Burst Mode RF PA implemented on PCB

Figure 3a shows the measurement results for the output power for different duty cycles with an envelope frequency, f_{burst}, of 5MHz. These measurement results demonstrate the correctness of the relationships between the duty cycles and the in-band and out-of-band power as earlier stated in equations (1-3). Measurement and simulation results of the efficiency performance of this Class E Burst Mode RF PA are provided in figure 3b. The measured efficiency curve, $\eta_{tot}(meas)$, for the total output power, P_{tot} approximates the ideal flat efficiency curve. This curve is measured with a 50Ω-wideband load and the efficiency η_{tot} is calculated by the ratio of total output power by the total DC power consumption of the PA. When this switching amplifier sees a 50Ω-wideband load, this results in the dissipation of all out-of-band power and the measured efficiency curve, $\eta_{inb}(meas)$, shows that the behavior is exactly similar to the traditional Class B efficiency, as proven in section 2 and illustrated in figure 3b.

The key issue to improve the efficiency curve and push it towards the ideal efficiency curve, is by connecting a narrow band-pass filter to the drain node of the switching amplifier. Due to insertion of the narrow band-pass filter, the out-of-band impedance seen by the LDMOS transistor is increased significantly. In this case, the ratio of the out-of-band power by the total output power generated by the transistor is now reduced to a minimum. This also means that the switching mode power amplifier is almost only generating the desired in-band signals at peak efficiency. The curves, $\eta_{inb\_filter}(sim)$ and $\eta_{inb\_filter}(meas)$, illustrate the efficiency enhancement that is offered by a Burst Mode PA compared to the conventional Class B amplifier. Figure 3b shows the efficiency versus output power of the Burst Mode RF PA. A peak efficiency of 78% and an output power of 28.5dBm are measured. Moreover, figure 3b clearly demonstrate the efficiency enhancement of the Burst Mode RF PA for both simulation and measurement. The efficiency curves of the Class A and Class B amplifiers are added in the figure with a dashed line. Both the measured and simulated efficiency performance of the Burst Mode amplifier show an increase of at least 10% in efficiency for every duty cycle than the conventional Class B and more than 30% compared to the Class A performance. Furthermore, an efficiency enhancement of 11.5% at 6dB power back-off is reached compared to the conventional Class B amplifier.



(a) Output power (mW) versus duty cycle (%)

(b) Efficiency (%) versus output power (mW)

Figure 3: Measured and simulated efficiency and output power of the switching mode PA

There is a power charge-discharge during the start and during the end of the burst which is independent of the duty cycle of the input signal and illustrated in figure 2b. Due to this power loss, there is a reduction of the peak efficiency at lower duty cycles, as illustrated in figure 3b. By increasing the ratio of the envelope burst frequency, f_{burst}, by the operating pulse frequency, f_{rf}, the efficiency is improved again at the lower duty cycles.

4 Conclusion

In this paper, the burst mode operation is proposed as an efficiency enhancement technique for RF amplifiers. The operation modes and the efficiency of the RF switching amplifier is investigated and the performance clearly showed an efficiency improvement over the traditional Class B approach. As a proof of concept, a Class E switching amplifier was constructed on PCB FR4 and the measurement results show a peak efficiency of 78% and 28.5dBm output power and an efficiency improvement of 11.5% at 6dB power back-off compared to the Class B performance is demonstrated.

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