WIDEBAND CLASS B AMPLIFIERS FOR SPLIT FREQUENCY ENVELOPE MODULATED RF POWER AMPLIFIERS

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Abstract- Envelope modulation is an efficient means of amplifying high dynamic range RF signals like LTE. Overall efficiency is the product of the RF amplifier's and the envelope modulator's efficiencies. In the split frequency modulator architecture, the linear amplifier has the largest impact on overall performance. This paper examines a number of linear amplifier architectures. For high efficiency, a class G complementary current-mode amplifier achieves 72% modulator efficiency at 17W output power with a 3MHz bandwidth LTE signal. For bandwidth a class B totem pole amplifier achieves 62% efficiency at 9W output power with a 20MHz bandwidth LTE signal.

I. Introduction

To achieve spectral efficiency contemporary communications standards like the 3GPP Long Term Evolution (LTE) [1] have adopted orthogonal frequency division multiplexing (OFDM) modulation. Spectral efficiency however comes at the expense of a high peak-to-average power ratio (PAPR) – up to 10dB for the LTE downlink signal. Conventional linear class B RF power amplifiers (PA) have a theoretical maximum efficiency of 38% when subjected to this type of signal, and often significantly less [2]. This low efficiency translates to high running costs for network operators and short battery life in mobile terminals.

Envelope modulation can dramatically increase PA efficiency by tracking the PA supply voltage in harmony with the envelope of the RF signal [3]. This ensures that the PA always operates in an efficient region of its transfer characteristic. Since overall system efficiency is the product of both the modulator and the RF PA, both need to achieve a high performance. The split frequency architecture achieves this by breaking the envelope signal into: a low frequency DC component and a high frequency AC one [4] as shown in Figure 1. The AC and DC components are combined by a frequency selective network composed of $C_{COMBINE}$ and $L_{COMBINE}$, which have the same cut-off as the input high-pass (HP) and low-pass (LP) filters.

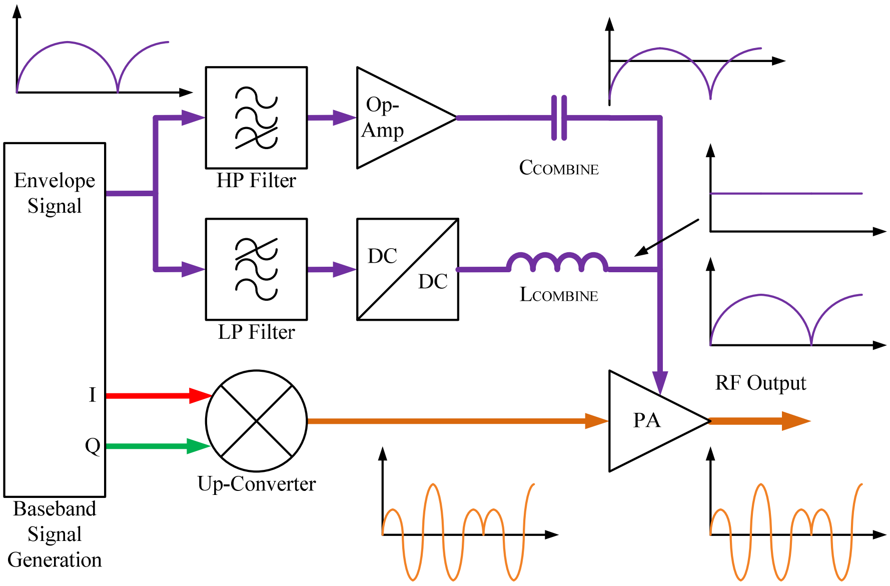
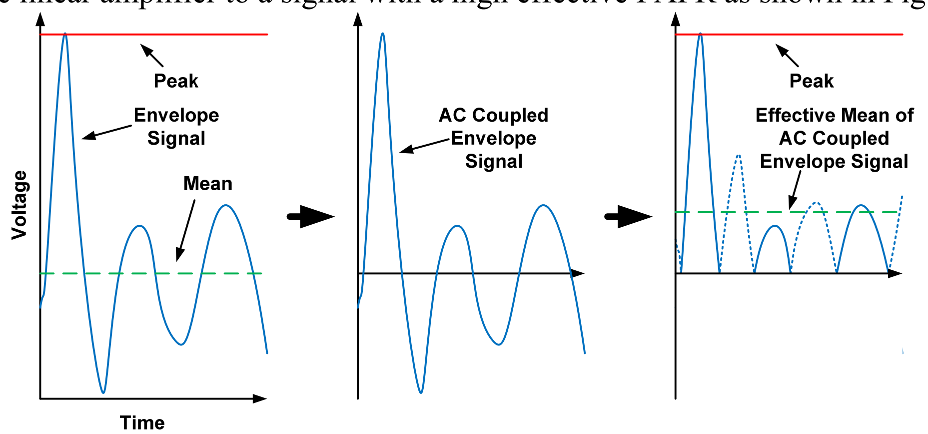


Figure 1. Envelope modulated RF PA

II. Split Frequency Envelope Modulator

Simulation of the LTE signal reveals that 80% of the envelope signal's power resides at DC [4] with the AC component accounting for the remaining 20%. This allows the envelope signal to be efficiently amplified by a switched mode power supply (SMPS) for the DC component, and a linear amplifier for the AC. Splitting the envelope signal in this way subjects the linear amplifier to a signal with a high effective PAPR as shown in Figure 2.



(a) (b) (c)

Figure 2. (a) Original envelope signal, (b) AC component of envelope signal (c) effective PAPR of AC component of envelope signal.

It is found, that when the original envelope signal is clipped to a PAPR of 7dB, the effective PAPR seen by the linear amplifier is 13dB. Assuming the linear amplifier is a standard class B amplifier its resulting efficiency will theoretically be 22%. Combined with a 95% efficient SMPS, overall modulator efficiency is calculated as 56% using [5]:

$$\eta_{EM} = \frac{100}{\left(\frac{\alpha}{\eta_{SMPS}} + \frac{1-\alpha}{\eta_{LA}}\right)} \tag{1}$$

Where LA represents the linear amplifier and α the DC power component of the envelope signal (0.8 for 80%). If however linear amplifier efficiency were increased by 10% to 32%, overall efficiency would be 66%. Therefore the linear amplifier has a large impact on EM efficiency.

III. Class B Push-Pull Amplifiers

Low frequency class B amplifiers usually consist of a matched pair of complementary power transistors as shown in Figure 3 (a). Matched pairs are generally not available for high frequencies, and also suffer from shoot-through-current due to their turn-off delay causing the conduction cycles to overlap. An alternative which partially overcomes this is the complementary current mirrors [6] as shown Figure 3 (b).

At RF frequencies the transformer coupled amplifier of Figure 3 (c) is common since the transistors are of the same polarity. This is capable of multi-decade bandwidth [7]. The bandwidth is defined by the input and output transformers, which also take up a large board area and are expensive to manufacture.

The output transformer can be removed by stacking the transistors in a totem pole configuration shown in Figure 3 (d) [8]. This can be further improved by using an active phase splitter on the input as shown in Figure 3 (e) [9].

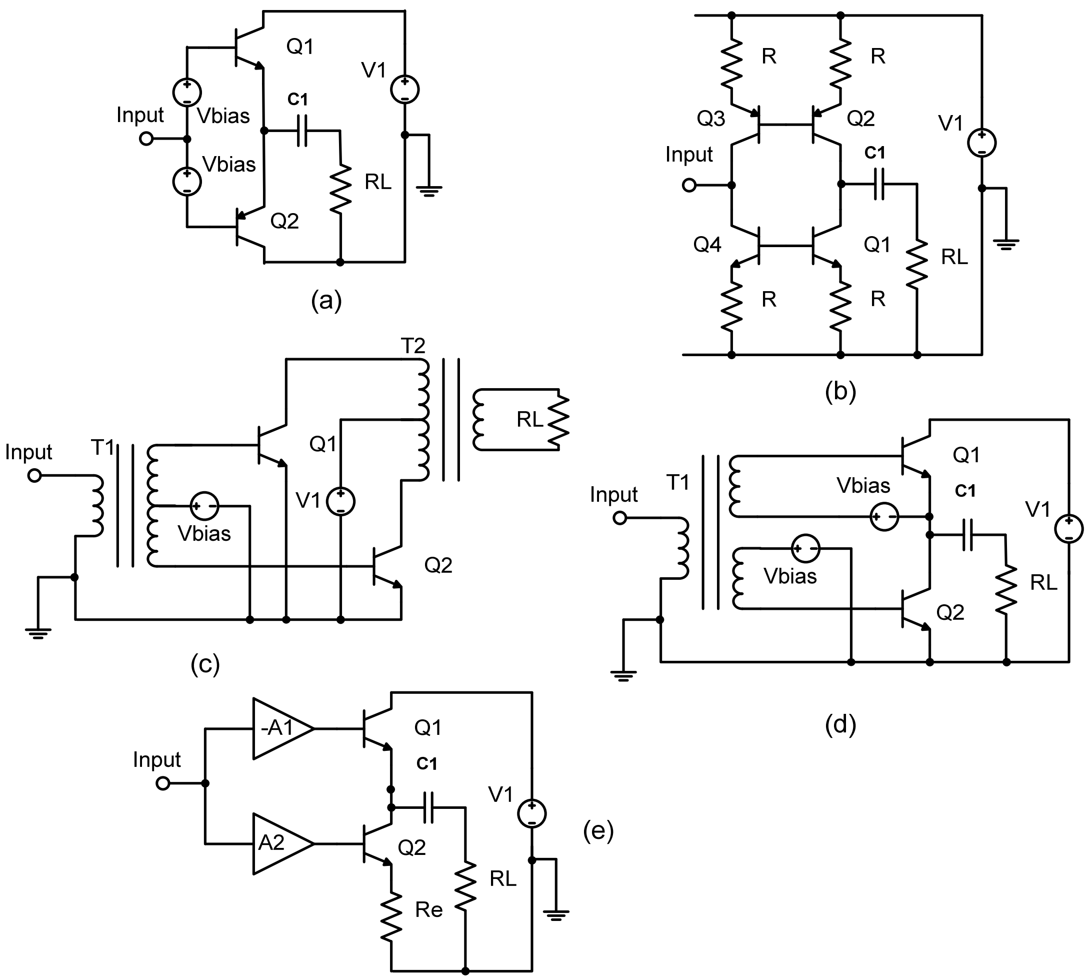
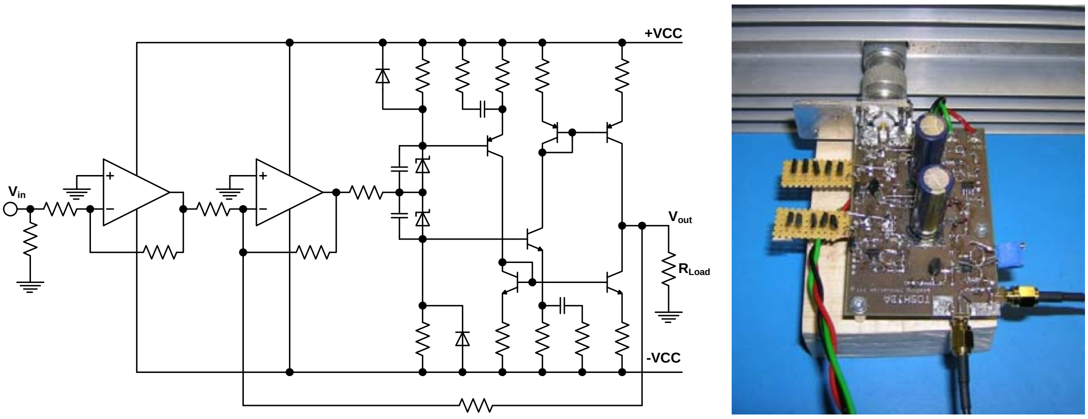


Figure 3. Class B amplifiers (a) emitter follower, (b) current mode, (c) transformer coupled (d) totem pole, (e) totem pole with active phase splitter.

IV. Complementary Current Mirror Amplifier

A simplified schematic of a current mirror amplifier is shown in Figure 6 (a). The output stage consists of complementary current mirrors; one formed from NPN transistors to provide the negative excursions and another from PNP provide the positive excursions. Class B biasing is achieved by a zener diode biasing network [10]. A photograph of the prototype is shown in Figure 6 (b).

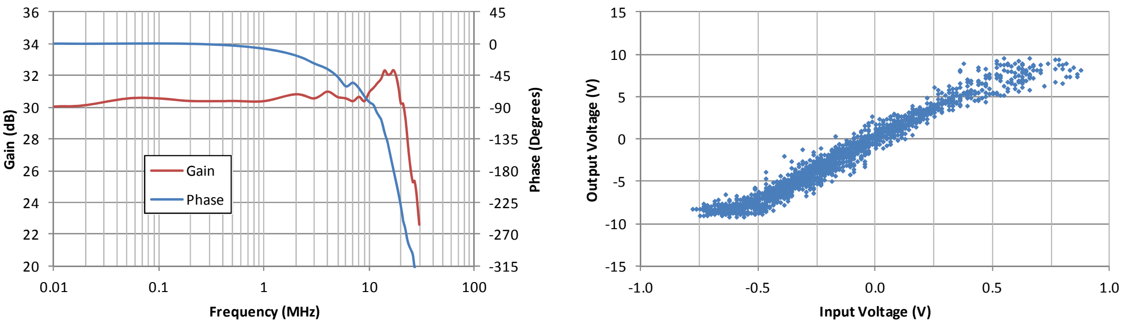


(a) (b)

Figure 4. Current mirror amplifier (a) simplified schematic and (b) photograph.

Practical Results

Under quiescent conditions the current consumption was 194mA with 15V bipolar power supply. A small signal bandwidth of 24MHz was recorded as shown in Figure 5(a). When a 3MHz bandwidth LTE envelope signal is applied to the amplifier, an efficiency of 19.1% at 2.2W into a 10Ω load was achieved. The input output transfer response of this is shown in Figure 5 (b). The smearing of points is due to the amplifier's phase shift. Clipping is visible at both the top and bottom of the transfer characteristic.



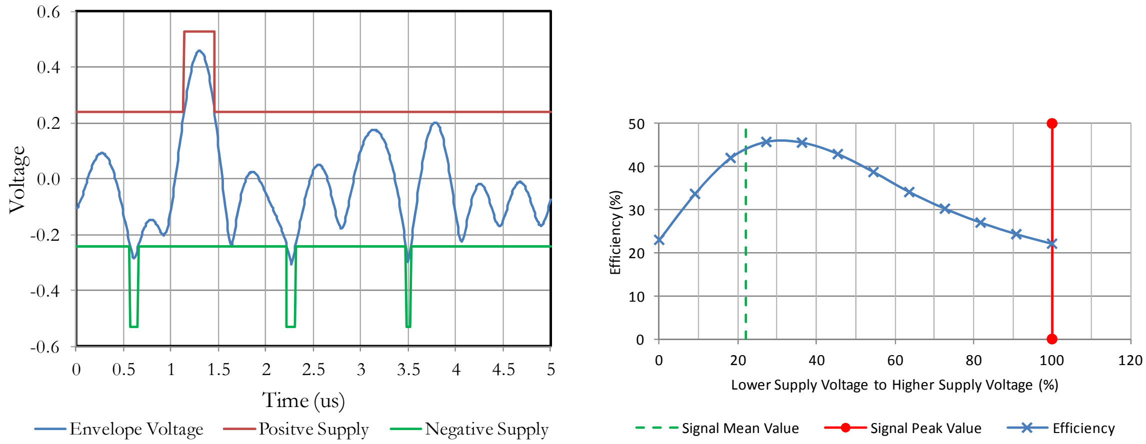
(a) (b)

Figure 5. (a) Small signal response and (b) transfer response with a 3MHz bandwidth LTE envelope signal.

V. Class G Amplifier

Although the linear amplifier is only responsible for 20% of the envelope signal's power, due to its low efficiency, it typically consumes the same amount of power as the SMPS. Adopting a class G architecture – whereby current is drawn from two or more power supplies dependant on the envelope signal's instantaneous value – can dramatically increase efficiency

[11]. Generally only two bipolar power supplies are used [12]. Figure 6 (a) shows a simplified example of this. Efficiency depends on the ratio of the magnitude of the two power supplies. The lower magnitude supply voltage is selected to provide current most of the time, and the higher one only during the peaks. The theoretical efficiency with a 3MHz bandwidth LTE envelope signal is shown in the Figure 6 (b) where the envelope has been clipped at 7dB and the lower power supply voltage is swept relative to the higher one.

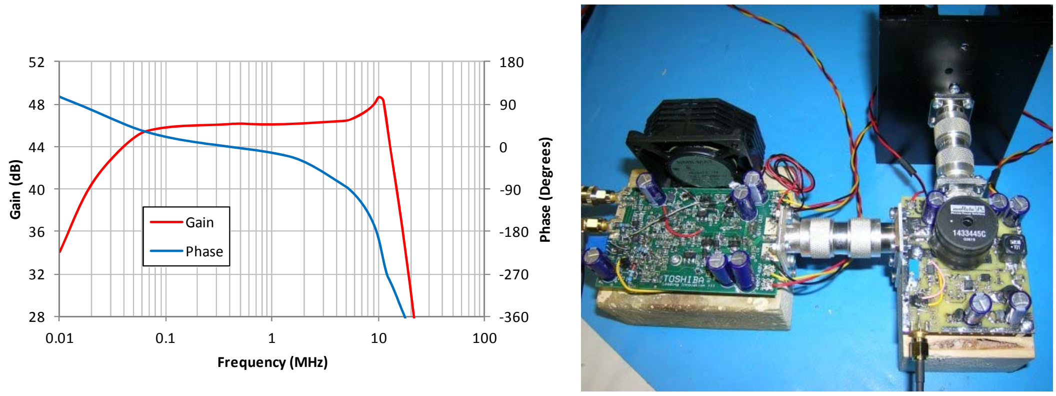


(a) (b)

Figure 6. (a) Class G amplifier operation and (b) efficiency versus voltage ratio.

Class G Amplifier Results

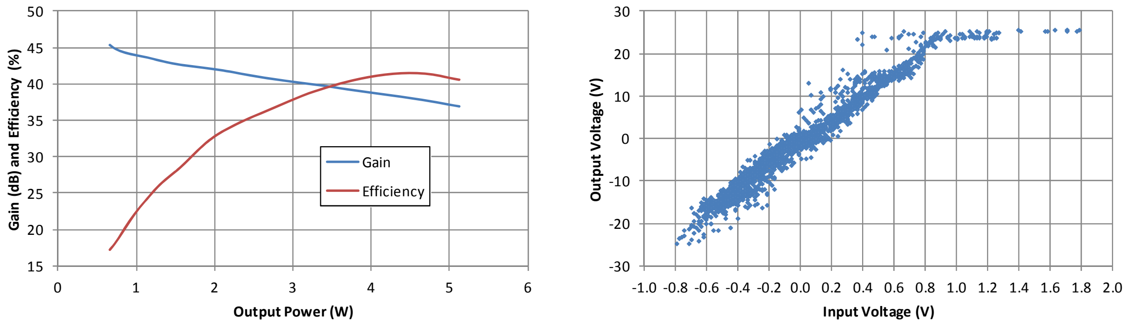
A parallel class G amplifier was developed from two of the current mirror amplifiers discussed above, with their outputs connected together by blocking diodes [11]. The inner amplifier responsible for supplying current during small envelope signal amplitudes was biased into class B and the outer one into class C. The small signal bandwidth of the amplifier was 9.5MHz as shown in Figure 7 (a) with a 33Ω load. A photograph of the amplifier connected as an envelope modulator is shown in Figure 7 (b).



(a) (b)

Figure 7. (a) Small signal response and (b) photograph of the complete modulator with class G Amplifier on the left, SMPS on right and resistive load above SMPS.

The power sweep with a 3MHz LTE envelope signal is shown in Figure 8 (a). The transfer response at the target output power of 3.3W is shown in Figure 8 (b). Under these conditions the efficiency was 39%; double that of the class B current mirror amplifier.



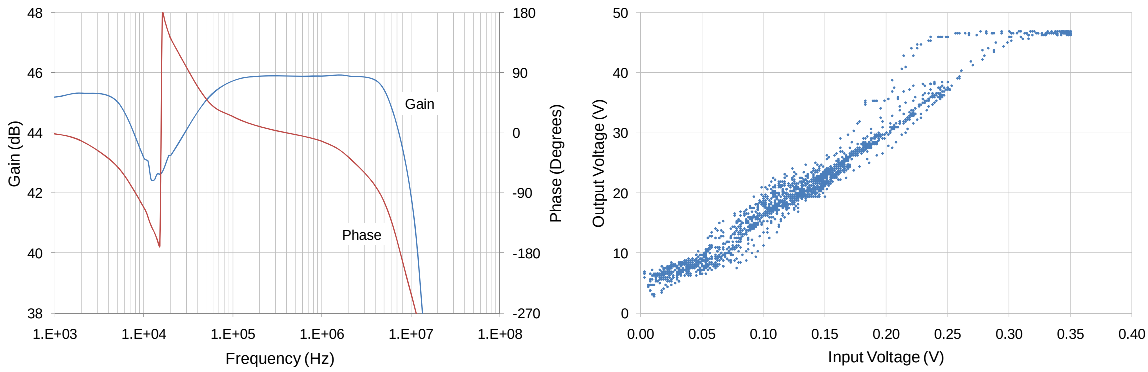
(a) (b)

Figure 8. (a) Power sweep of class G amplifier and (b) large signal response with 3MHz bandwidth LTE signal.

Clipping is visible in Figure 8 (b) at the peaks. Distortion visible as the signal passes through the origin and at the switching points. Figure 7. (a) Small signal response and (b) photograph of the complete modulator with class G Amplifier on the left, SMPS on right and resistive load above SMPS.The effect of transistor storage time is also present, as the transistors come out of saturation in the upper right quadrant.

Envelope Modulator Results

An accompany SMPS achieved 95% efficiency under target conditions. Traditionally, the SMPS output filter is designed for a low cut-off frequency to reduce output noise. The output smoothing capacitor and control loop of this SMPS were modified to increase its bandwidth to 20kHz. The small signal frequency response of the complete modulator is shown in Figure 9 (a).



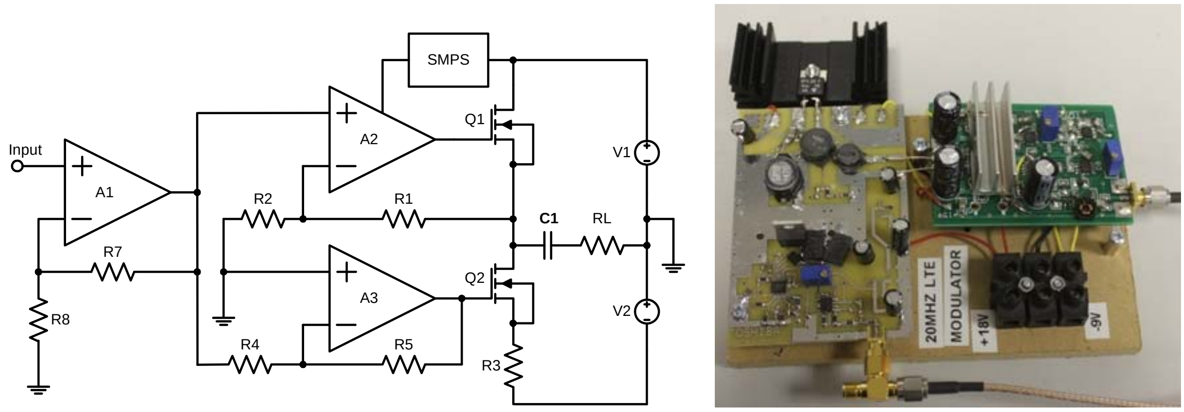
(a) (b)

Figure 9. (a) Small signal response and (b) transfer response of complete modulator.

With a 3MHz LTE envelope signal applied the RMS power was 16.6W into the 33Ω load. The DC (mean voltage) component was measured at 13.3W, representing an α of 0.80. Overall efficiency was 71.5% with a peak voltage of 46.5V, equivalent to a PAPR of 7.3dB. The modulator's output voltage versus input voltage transfer characteristic under these conditions is shown in Figure 9 (b). The modulator has also been combined with an RF PA, where it achieved 42% efficiency in envelope tracking mode and 44% in envelope elimination and restoration mode [13].

VI. Totem Pole Amplifier

Although the current mirror architecture achieved high efficiency when combined with class G techniques, its bandwidth was limited. This is largely due to the complementary bipolar output transistors. The totem pole architecture shown in Figure 3 (e) overcomes this by using the same polarity of output device to both sink and source current. For this work RF LDMOS transistors were used. A simplified schematic of the totem pole amplifier is shown in Figure 10 (a), and a photograph of the complete modulator in Figure 10 (b).



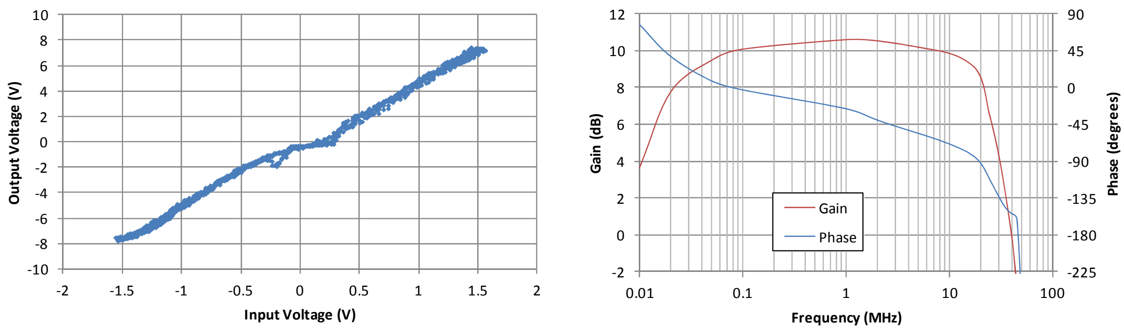
(a) (b)

Figure 10. (a) Simplified schematic and (b) photograph of complete 20MHz modulator with totem pole amplifier on right, SMPS on left and load above the SMPS.

As seen in Figure 2 the AC component of the envelope signal is asymmetric with the positive excursions significantly larger than the negative ones. Up to this point equal magnitude bipolar supply voltages have been used. To increase efficiency the totem pole amplifier used a negative supply voltage of a lower magnitude than the positive.

Totem Pole Amplifier Results

The amplifier's transfer response with a 1MHz sine wave input signal into a 7.5Ω load resistance is shown in Figure 11 (a) and the small signal response in Figure 11 (b).



(a) (b)

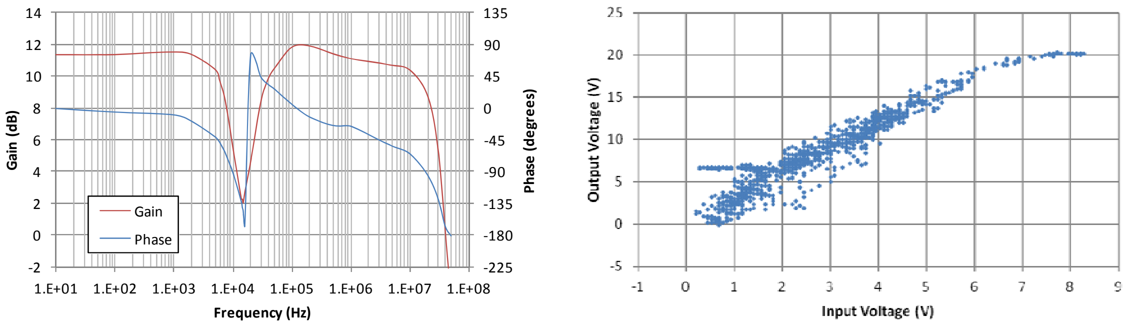
Figure 11. (a) Transfer response with a 1MHz sinusoid and (b) small signal response.

The cross-over distortion typical of class B amplifiers is visible in Figure 11 (a) as the signal passes through the origin. The gains of both upper and lower amplifiers are equal – as indicated by the slope of the positive and negative excursions – even though they operated in different modes.

The amplifier's bandwidth was 23MHz, which is sufficient for passing the envelope of a 20MHz bandwidth LTE signal. At the 2W target output power 31% efficiency was achieved with the envelope signal applied. This is higher than that of the current mirror amplifier due to a lower quiescent current and the asymmetric power supply voltages.

Envelope Modulator Results

A compatible SMPS based around the National Semiconductors LM25088 achieved 89% efficiency at the target output power of 8W. It was optimised for a bandwidth of 22kHz. The overall envelope modulator bandwidth extended from DC to 23MHz as shown Figure 12 (a), with a cross-over frequency of 15.3kHz. The transfer response with the 20MHz bandwidth LTE envelope signal is shown in Figure 12 (b).



(a) (b)

Figure 12. (a) Small signal response and (b) transfer response of Complete EM.

Under these conditions the complete modulator achieved 61.6% efficiency at 9.3W output power. The AC component was measured as 1.8W, resulting in a totem pole amplifier efficiency of 29%. α was therefore 0.81 and the measured output PAPR 8.5dB. Further details can be found in [14].

VII.Conclusion

Envelope modulation has the potential to dramatically increase the efficiency of an RF PA when high PAPR signals like LTE are involved. The split frequency envelope modulator architecture has proven itself a low cost and efficient means of achieving this provided the linear amplifier can meet the right requirements of: output power, efficiency and bandwidth.

Two different class B architectures for the linear amplifier are considered in this paper. One is the complementary current mirror which when class G techniques are incorporated produced a 71.5% efficient modulator with an output power of 16.6W and a 3MHz bandwidth input signal. The second is the totem pole amplifier which resulted in a 61.6% efficient when supplying 9.3W with a 20MHz bandwidth signal.

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