Systematic Waveform Engineering Enabling High Efficiency Modes of Operation in Si LDMOS at both L-band and S-band Frequencies

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Abstract — This paper demonstrates that by robust waveform engineering it is possible for high power Si LDMOS to achieve very high efficiency at frequencies up to 2.1 GHz. Class F amplifier operation was realized in a 5W LDMOS device by the successful application of robust waveform engineering procedures; undertaken at the current generator plane. The peak power added efficiency was found to be 78% at 0.9GHz and 77% at 2.1GHz. In both cases the RF waveforms were optimized in terms of the gate voltage, fundamental and harmonic impedances. The main difference at 2.1GHz was the change in fundamental impedance to a more reactive impedance to compensate for the dynamic device output capacitance. To the authors' knowledge this is the highest efficiencies reported in the literature for Si LDMOS devices at 2.1GHz.

Index Terms — High power, MOSFETs, power amplifiers.

I. INTRODUCTION

In the current climate of energy conservation, higher running costs and limited energy supplies there is a great need to produce highly efficient power amplifiers. This is especially applicable for high power applications such as radar or mobile phone basestations where the amplifiers are typically outputting in excess of 40dBm.

One such high efficiency implementation is the Class F amplifier that allows for a maximum efficiency of 100% but also allows for maximum output power. The optimal design of a class F amplifier is done through waveform engineering at the device output [1] and this has been successfully achieved at low power levels in an on wafer environment [2] - [3].

However, the use of waveform engineering in high power devices requires the consideration of extra factors which can significantly alter the waveforms [4]. These are the packaging of the device and the measurement system impedance. Once these affects are negated, waveform engineering can again be applied. In this paper the successful use of waveform engineering has been demonstrated on a 5W Si LDMOS device supplied by Freescale Semiconductor. The resulting robust waveform engineering was undertaken at both 0.9GHz and 2.1GHz using the high power active harmonic load pull measurement system developed at Cardiff University [5].

There is a large amount of literature reporting high efficiency LDMOS designs with power added efficiencies above 75% [6]. However, this has only been achieved at frequencies around 1.2GHz. At frequencies approaching S-band the efficiencies typically reported are a lot lower and in the range of 60-65% [6] which is effectively no better than a

class B amplifier. This paper outlines how a proven high efficiency design process [1] can be applied to the latest Si LDMOS devices at S-band frequencies to achieve efficiencies close to theoretical class-F operation under band limited conditions.

II. DE-EMBEDDING TO THE CURRENT GENERATOR PLANE

A key requirement for waveform engineering is for procedures to be applied at the current generator plane. Only at this plane is there a direct correlation of the waveforms to the DCIV plane and this also allows for extraction of the device output capacitance which needs to be resonated out if an open circuit is to be presented at the current generator plane. This was done by de-embedding the measured I-V waveforms to the current generator plane. This required the subtraction of the displacement currents and voltages generated by the device and package parasitic components [4].

Fig. 1 Device and package parasitic circuit model

The package and device model, which was employed for RF waveform de-embedding, is shown in Fig. 1, and consists of a manifold/bond pad capacitance, bonding wire inductance and a non linear device output capacitance [7]. The package model allowed for the calculation of impedances required at the measurement plane to present the desired impedances at the current generator plane as shown in Table I. A linear capacitance was used in an s-parameter simulation, thus allowing engineering of class F behavior at the current generator plane.

TABLE I

SUMMARY OF THE IMPEDANCES REQUIRED AT THE MEASUREMENT PLANE TO PRODUCE SHORT AND OPEN CIRCUIT TERMINATIONS AT THE CURRENT GENERATOR PLANE

Frequency	2 nd Short	2 nd Open	3 rd Short	3 rd Open
0.9GHz	0-6.8j Ω	0+48.7j Ω	0-9.8j Ω	0+31.5j Ω
2.1GHz	0-20.1j Ω	0+10.1j Ω	0-23j Ω	0+1.2j Ω

III. CLASS F INVESTIGATION

A. Gate sweeps

Class F behavior was achieved through a systematic investigation outlined in [1]. This procedure started with a gate sweep of the device with a real impedance at the fundamental and short circuits at the second and third harmonics. The gate sweep measurement located the appropriate bias condition to null the most significant odd harmonic (i.e. 3rd harmonic) so that it appears only in the voltage waveform, minimizing dissipated energy and thus enhancing efficiency. This was done at 0.9GHz and 2.1GHz, the results for 0.9GHz are shown in Fig. 2.

Fig. 2 Gate voltage sweep at a fundamental frequency of 0.9GHz with the second and third harmonics set to short circuits

The gate sweep at 0.9GHz shows that there is a clear third harmonic minimum at a gate voltage of 2.37V, which is slightly above pinch off. At 2.1GHz the third harmonic minimum does not occur at the same gate voltage. As well as that the third harmonic current minimum is no longer as clearly defined as it was at 0.9GHz. In this case a minimum third harmonic current is observed at a gate voltage of 2.25V. The reason for this could be due to the relatively low f_T which is in the region of 7.5GHz, which starts to affect the harmonic composition of the current waveform when operating at 2.1GHz.

B. Harmonic Optimization

The harmonic terminations applied at the current generator plane were determined after taking the parasitic network into account. However, due to uncertainties in determining the parasitic components, second and third harmonic phase sweeps, at the two frequencies of operation were conducted,

with a constant magnitude set to one. To begin with a second harmonic sweep was done with the third harmonic passively terminated to 50 Ω . Once the optimum was determined for the second harmonic a similar phase sweep was done around the third harmonic with the second harmonic now locked to its optimized value. The results are shown in Figs. 3 and 4.

At both frequencies it can be seen that the sensitivity of the second harmonic is very low. This is due to the large device output capacitance, which effectively already provides the required low termination to the current generator. However, in both cases a peak in efficiency is found. At 0.9GHz this is occurring at 0-14.4j Ω and at 2.1GHz this occurs at 0-24j Ω . These agree well with the values shown in Table I.

Fig. 3 Phase sweeps at the measurement plane of the second and third harmonic impedances at a fundamental frequency of 0.9GHz

Fig. 4 Phase sweeps at the measurement plane of the second and third harmonic impedances at a fundamental frequency of 2.1GHz

The third harmonic phase sweep, used to locate an open, shows a higher level of sensitivity than observed for the second harmonic. This is due to the requirement of resonating out the device output capacitance, which becomes difficult at higher frequencies. This is confirmed by the increased sensitivity of the efficiency at 2.1GHz where there is a larger variation in efficiency. Peak efficiency at 0.9GHz is found at $0+28j\Omega$ and $0+3.5j\Omega$ at 2.1GHz. As before, these are in agreement with the simulated values shown in Table I.

C. Fundamental Impedance Sweep

Now that the design has been optimized in terms of its harmonic current and voltage composition, the next step was to enhance the performance of the device at the fundamental. This was done by varying the load presented at the fundamental frequency of operation. The desired real impedance was achieved at the current generator plane by accounting for the package network. This real intrinsic load was then swept over a range of values to determine the optimum fundamental impedance in terms of power added efficiency. Typically, higher drain efficiencies are possible at high fundamental load impedances as the effect of the knee is minimized. However, in this case the power added efficiency (PAE) is used to ensure that the amplifier has sufficient gain. The results are shown in Fig. 5.

The results show that there is an expected decrease in power with load increase but the PAE only noticeably increases up to a fundamental load impedance of 110Ω . For this reason a fundamental load of 110Ω is chosen as this also provides 36dBm (4W) of output power. This impedance of 110Ω at the current generator plane was found to be $54.2 + 52.6j\Omega$ at the measurement plane.

At 2.1GHz, the same procedure was applied but it was quickly realized that a real only fundamental impedance was no longer easily achievable. This was due to the effect of the dynamic capacitance, which becomes more prevalent at higher frequencies. The dynamic device output capacitance is a function of the drain voltage [7] and this can not be accounted for using an s-parameter simulation. To minimize the error the ‘average’ capacitance was determined using the MET [8] model of the device. This was done at the fundamental frequency of operation and this value was inserted into the s-parameter simulation. The measured results of the fundamental load sweep at the current generator plane are shown in Fig. 6.

The results in Fig. 6 outline the same performance variation as seen in Fig. 5 but with a lower gain. This is expected due to the relatively low f_T of the device. This in turn affects the PAE of the device. As can be seen in Fig. 6 the drop in PAE is about three to four percent compared to the results at 0.9GHz.

To confirm that this was the optimum impedance a high-density fundamental load pull sweep was conducted. The optimum impedance for PAE was found to be $13.9 + 30.1j\Omega$. This was found to be a complex impedance of $99.7 + 25.9j\Omega$ at the current generator plane which is close to the 110Ω

fundamental impedance used at 0.9GHz. The reactive component is possibly due to the complex impedances being presented at the higher harmonics. This occurs due to the 50Ω system impedance at the higher harmonics being transformed to complex impedances at the current generator plane. Rhodes [9] has theoretically outlined that the optimum impedance for efficiency changes when the higher harmonics are terminated into complex impedances. This new impedance was then used to measure the performance of the device in class F.

Fig. 5 Fundamental real only load sweep at the current generator plane measured at 0.9GHz

Fig. 6 Fundamental real only load sweep at the current generator plane measured at 2.1GHz

IV. CLASS F RESULTS

The device was put into the conditions at the measurement plane as outlined in Table II. The results obtained at 0.9GHz are shown in Fig. 7. The PAE obtained at 1dB compression was 77.2% whilst delivering 36dBm of output power to the load. A peak PAE of 78% was measured with the device 4dB into compression.

TABLE II

SUMMARY OF DEVICE SETTINGS FOR CLASS F PERFORMANCE

Frequency	V _g (V)	Z(f ₀)	Z(2f ₀)	Z(3f ₀)
0.9GHz	2.37	54.2 + 52.6j	0-14.4j Ω	0+28j Ω
2.1GHz	2.25	13.9 + 30.1j	0-24j Ω	0+3.5j Ω

The waveforms, at 1dB compression are shown in Fig. 8. The waveforms confirm that class F behavior was obtained at

the current generator plane. The voltage waveform is shown to be 'squared' in shape and the current is half rectified.

Fig. 7 Performance of the device in class F at 0.9GHz

Fig. 8 Measured voltage and current waveforms at the current generator plane at a fundamental frequency of 0.9GHz

Fig. 9 Performance of the device at 2.1GHz

Fig. 10 Measured voltage and current waveforms at the current generator plane at a fundamental frequency of 2.1GHz

The results obtained at 2.1GHz are shown in Fig. 9. The performance is similar to that obtained at 0.9GHz, with 77.1% PAE at 1dB compression with 35.9dBm of power being delivered to the load. The main difference is that the flat peak efficiency region found at 0.9GHz was not replicated at 2.1GHz. The waveforms are shown in Fig. 10.

The voltage waveform is shown to be square in shape as at 0.9GHz and the current is half rectified. However there is a slight reduction in the third harmonic voltage component

V. CONCLUSIONS

Through the use of de-embedding and active harmonic load pull, the demonstration of a Si LDMOS device in class F operation has been shown to produce record levels of efficiency at S-band frequencies. De-embedding to the current generator plane was essential to allowed for waveform engineering to be undertaken at the current generator plane. This also allows for direct comparison of the device performance at the different frequencies of operation. This has been confirmed by comparing a similar investigation conducted at 0.9GHz and good agreement was found in terms of performance and in the current and voltage waveforms.

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