Highly Efficient Operation Modes in GaN Power Transistors Delivering Upwards of 81% Efficiency & 12W Output Power

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Development of a 'first-pass' inverse class-F design procedure has obtained very high efficiency device performance, at high power levels…

The Motivation – High Efficiency PA Modes

- **Require a systematic design and realisation process to overcome time-consuming and multi-iterative PA designs**
- Design of complex PA modes → Requirement for harmonic characterisation / measurement capability
- **Need a process for rapidly optimising harmonic impedances**

The Solution – A Process for Rapid PA Optimisation

- **Methodology has been developed for an effective, working design approach**
- Utilising Cardiff University's time-domain waveform measurement capability to engineer high efficiency waveforms and device performance
- **First pass design success, provided good prior stability analysis**
- Approaching theoretical optimum efficient device performance - 84.0% efficiency obtained at 2.1GHz operating with 40V DC rail

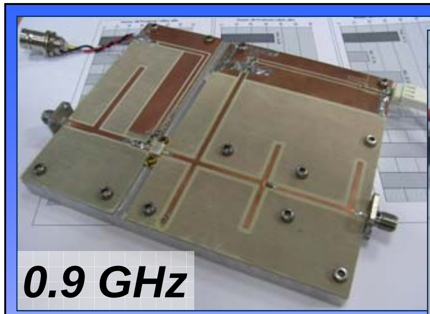
High power device characterisation/waveform engineering

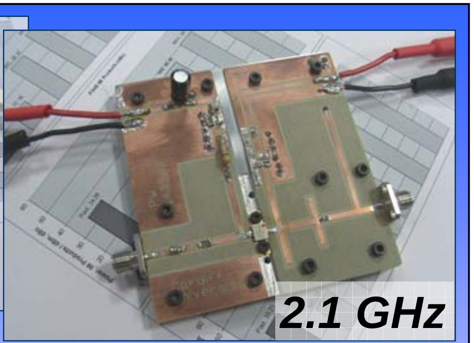
- A real measure of device performance intended for PA applications

Process has successfully yielded TWO 10W+ amplifiers operating at 80%+ efficiency using this FAST design approach!

Inverse class-F PA realisations

Extended work has made direct use of captured data for designs of complex PA modes → promising results following realisation of two high efficiency prototype PAs.


0.9 GHz


2.1 GHz

Performance Measures	**Device Measurements** (0.9GHz Fundamental)	**Realised PA** (0.9GHz Fundamental)
P1dB Output Power	38.6 dBm	38.1 dBm **(38.4dBm at the dev.)**
P3dB Output Power	40.6 dBm	40.4 dBm **(40.7dBm at the dev.)**
Max. Avail. Gain at P1dB	25.6 dB	24.2 dB **(24.5dB at the dev.)**
Drain Efficiency at P3dB	79.8 %	76.7 % **(82.2% at the dev.)**

Key Advantage: *Design **does not** require manufacturers non-linear device models!*

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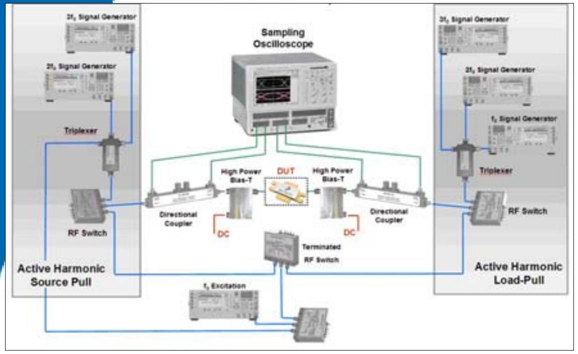
RF waveform engineering was used to obtain high efficiency inverse class-F waveforms at the device current generator (I_{gen}) plane…

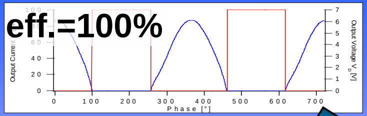
Waveform Measurement System

Calibrated Time-Domain Waveform Measurements
Active Load-Pull: Fundamental / Multi Harmonic



- *Time domain RF waveform capture*
- *High power active load-pull capability*
- *Independent control of fundamental, 2nd, 3rd harmonic terminations*

Inverse Class-F Theoretical Efficiencies



Ideal waveforms

Wave Shaping

- 5-harmonic terms in current waveforms (Imax. boundary)
- 2-harmonic terms in voltage waveform (active load-pull)

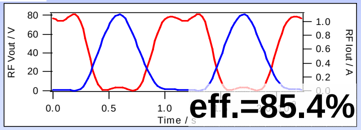
$$\eta_{voltage} \cdot \eta_{current} = 1.000 \times 0.854 = 0.854$$

$$\eta_{drain} = 100 \times \frac{V_{DC} - V_{knee}}{V_{DC}} \times 0.854$$

Approximations

- Bandwidth limitation factors
- DC Offsets
- Ability to generate perfect loads

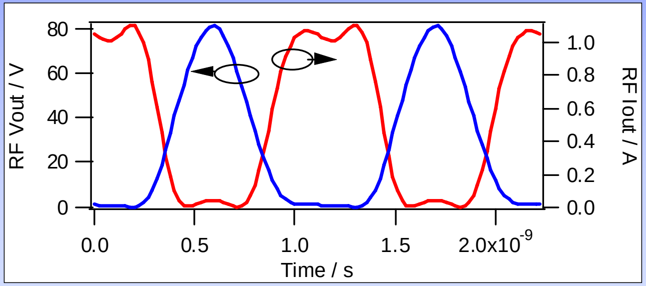
Practical waveforms



eff.=85.4%

Waveform Engineering Design Process

1. On-wafer techniques for optimising device performance have been adapted for use on high-power, packaged devices.
2. **By modeling output and package parasitics, it is possible to de-embed to the device plane and engineer theoretical waveforms inside the package.**
3. Perform high power measurements at calibrated package reference plane.
4. **Verification of performance established and compared with theory, quickly.**



10W GaN HEMT was used in this investigation to obtain high efficiency PA modes of operation, including inverse class-F.

Design procedure carried out at 0.9GHz AND 2.1GHz.

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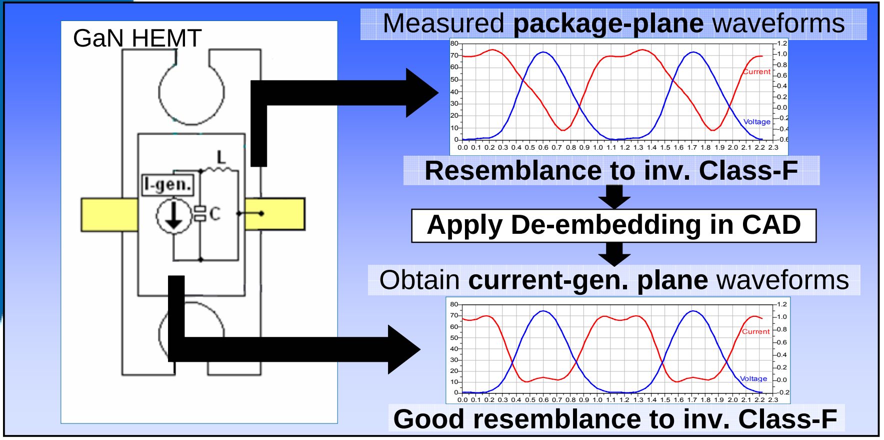
Drain efficiencies above 81% have been achieved at 0.9GHz and 2.1GHz for a wide band-gap gallium nitride (GaN) HEMT transistor and 12W fundamental output power…

Output Parasitic Modelling and De-embedding



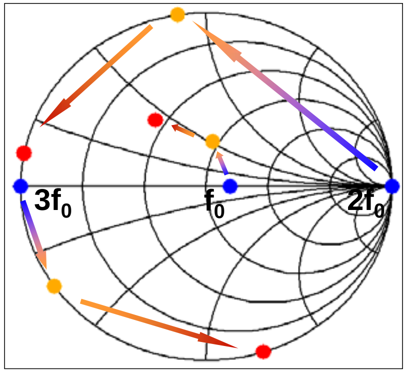
Measured **package-plane** waveforms

Resemblance to inv. Class-F

Apply De-embedding in CAD

Obtain **current-gen.** plane waveforms

Good resemblance to inv. Class-F



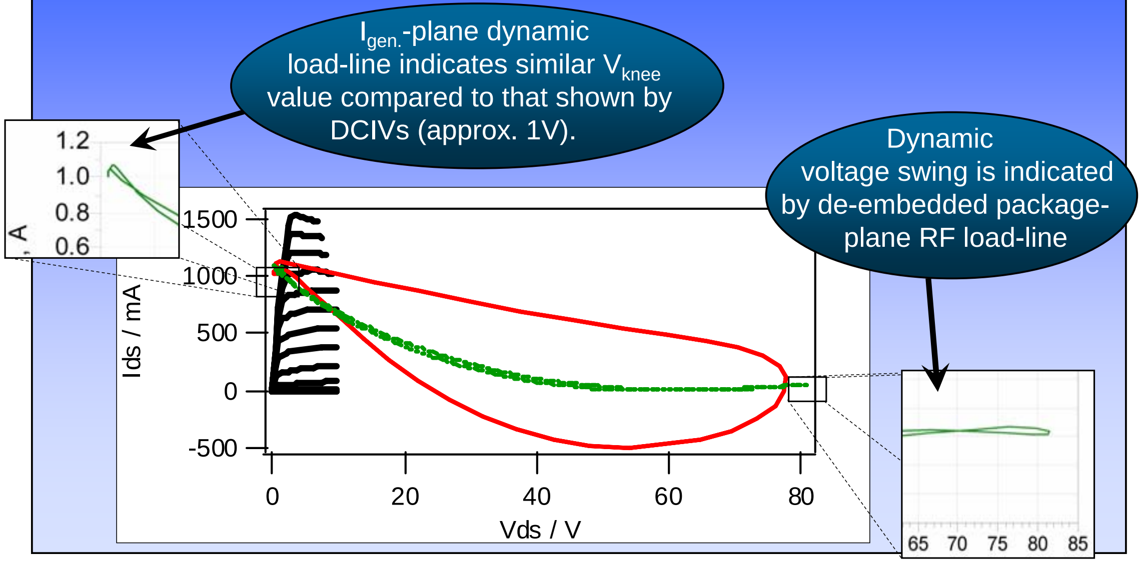
Utilise output parasitic model in predicting optimum impedances at any frequency, e.g. to obtain inverse class-F operation at the $I_{gen.}$-plane.

● **$I_{gen.}$-plane**
● **Package-plane 0.9GHz**
● **Package-plane 2.1GHz**

Device boundaries

Voltage offset or "walkout" effect is minimised by operating at lower drain current → Same output power through increased drain voltage swing → 1V voltage offset ("knee") in this study…

- De-embedding allows for correlation between the dynamic I-Vs and DCIV-plane which define the device boundaries



$I_{gen.}$-plane dynamic load-line indicates similar V_{knee} value compared to that shown by DCIVs (approx. 1V).

Dynamic voltage swing is indicated by de-embedded package-plane RF load-line

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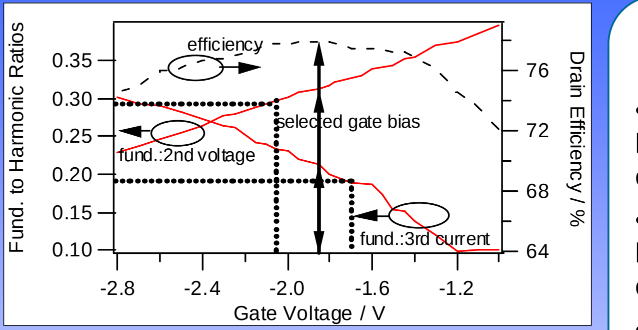
Investigations into improvements in drain efficiency through increases in drain bias voltage have yielded device drain efficiencies of up to 84% at 2.1GHz…

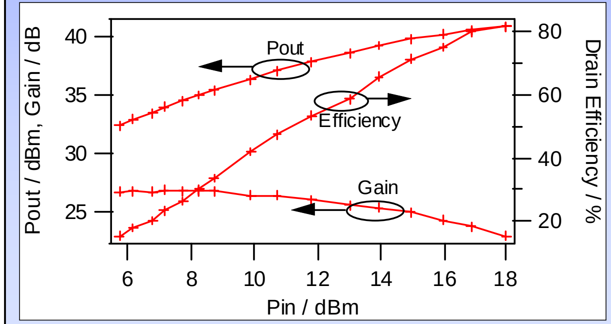
Performance Analysis at 0.9GHz

Gate Bias Sweeps and Results at 0.9GHz:

Gate bias sweep



Power sweep following optimisation



Maximally-Flat Ratios

- Require fund:2nd - harm. voltage ratio of 0.29
- Require fund:3rd- harm. current ratio of 0.18
- Resulting gate voltage = -1.85V

High Efficiency Performance

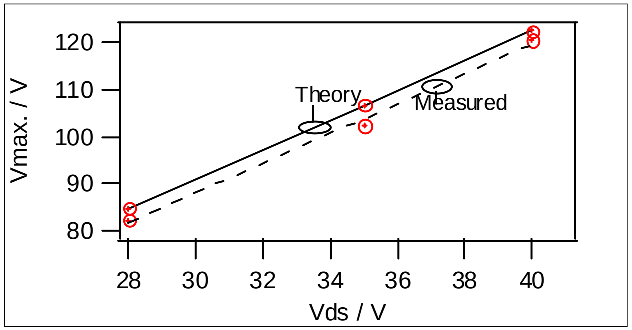
- 12Watts output power
- 22dB device gain.
- 81.5% drain efficiency

Inverse Class-F Scaled to 2.1GHz AND up to Vds of 40V

- RF voltage swing and DC rail relationship shows good theoretical agreement, according to eq. → $V_{\max.} = \pi \cdot \left(V_{DC} - V_{knee}\right)$

High Efficiency GaN at 2.1GHz

- Design process scales with frequency.
- High device breakdown limits allow for extending V_{ds} well beyond 28V.
- Efficiency extends to 84%!



Conclusions and Discussions

- *Successful 'first-pass' designs is now a reality.*
- ***Drain efficiencies of 84% have been obtained for optimised device operation at 2.1GHz operating with 40V DC rail***

  → Design procedure achieves scalable device performance!
- *Waveform engineering is a powerful tool in design of complex PA modes and achieving theoretical optimum device performance.*
- ***High output power and gain have not been compromised.***

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