Design and Verification of High Efficiency Power Amplifier Systems

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What is Nujira?

• Nujira makes Envelope Tracking Modulators that make power amplifiers more efficient.
• We are based in Cambridge (UK)
• Nujira was 10 years old last year
• We have over 70 employees, 34 of which have MATLAB licenses.
• We have over 200 patents covering Envelope Tracking Technology
• We have developed three major product lines:

Low Power
1 Watt

High Power
20 Watt

Ultra Power
KWatt
Contents

This presentation will cover the following:

• Envelope Tracking Principles
• Closing The Design Loop
• System Level Modelling
• RF Test System
• PA Characterisation
• Envelope Tracking IC validation
• Flexible Development Platform Development
• Summary
ENVELOPE TRACKING
PRINCIPLES
Envelope Tracking Principles

• Envelope tracking was first described over 60 years ago.

“Envelope tracking describes an approach to RF amplifier design in which the power supply voltage applied to the power amplifier is constantly adjusted to ensure that the amplifier is operating at peak efficiency for the given instantaneous output power requirements.”

• Nujira was the first company to produce a manufacturable implementation with our .H product line.
Envelope Tracking Principles

Fixed Supply

Envelope Tracking (ET)

RF

V supply

RF

PA

Antenna

Fixed PA Supply Voltage (Vs)

Dissipated As Heat

Transmitted RF Signal

Tracking PA Supply Voltage (Vs)

Dissipated As Heat

Transmitted RF Signal
Envelope Tracking Principles

• To achieve the best system efficiency, we need to determine the optimum V supply for each output power level.
• We call the mapping function between Pout and V supply a “Shaping Table”
CLOSING THE DESIGN LOOP
Closing The Design Loop

- We have a system level based development flow:

- The same approach is used in the development of Envelope Tracking Integrated Circuits (ETIC) and internal test equipment:
SYSTEM LEVEL MODELLING
We model the behaviour of key components to predict full system performance.

The PA model is based on data obtained using tools we have developed internally (PA Characterisation).

The original PA models were developed using ADS tools, but porting them to MATLAB resulted in quicker tools with greater dynamic range.

We use different modelling techniques for each of our Modulator product ranges.
System Level Modelling

• For the high and ultra power Modulators we have used Simulink to model the modulator behaviour.
  • These high level models have enabled us to optimise component values without excessive bench time.

• For the ET Integrated Circuit Modulators we use the Cadence design tools backed up with MATLAB functional models.
  • The MATLAB models provide much quicker results than the pure IC based tools.

• The following MATLAB toolboxes are used in the system level simulations:
  • Signal Processing
  • Communication Systems
  • DSP System
  • RF
RF TEST SYSTEM
RF Test System - Introduction

• This RF System Test Bench is used to:
  • Characterise PA behaviour
    • For use in system models and creating Shaping Tables
  • Measure system level parameters:
    • Efficiency, ACP, EVM, noise, tracking accuracy
    • For use in system and ETIC validation
RF Test System – Block Diagram

- The following shows the key software and hardware components:
RF Test System - Measurements

- The key to characterising PAs for ET is instantaneous measurements of power, current and voltage.
- We take instantaneous measurements at four points in the system.
  - (1)+(2) ➞ PA Gain/Phase
  - (3)+(4) ➞ Split Power

![Diagram of RF Test System]

- Envelope
- Modulator
- V supply
- PA
- Oscilloscope Channel#1
- Oscilloscope Channel#2
- Baseband ADC#1
- Baseband ADC#2

(1) RF Input ➞ PA
(2) RF Output ➞ PA
(3) Voltage ➞ Oscilloscope Channel#1
(4) Current ➞ Oscilloscope Channel#2
RF Test System – Evolving Requirements

• In the last year system complexity has increased considerably
• So we have produced one of the first multi band MIPI RF front end reference designs
RF Test System- Automation

Which has resulted in the following changes to the RF Test System:

• Added MIPI control for ETICs, PAs and switches.
• Added Multiple RF band measurement
• Added RF Noise measurement capabilities
RF Test System - Applications

- The software can be run in the following modes:
  - A compiled stand alone application for customers
  - Using the MATLAB Compiler
  - Manual control GUI for developers
  - ATE mode for design verification
- Which has saved over $2.0M in manual test costs to date
RF Test System - Reports

- The automated test software records test results in a repeatable manner, storing data on the network and MySQL database.
- A new automated report generator enables faster data analysis.

Equipment Measurements

Summary Sheets

Report Generator

Detailed Results Files

Results Plots
RF Test System - Calibration

- To ensure that repeatable and consistent results are obtained we have developed a series of RF bench calibration “Wizards”
- These are used to calibrate:
  - Oscilloscope measurement points for:
    - Modulator voltage and
    - Modulator current sense
  - RF power measurement points across frequency
  - Analogue envelope voltage levels
PA CHARACTERISATION
ET Surface Explorer

• ET Surface Explorer is a extension to the RF Test System that takes measurements across a range of PA operating points using a patented measurement technique.

• This enables us to create a surface describing power amplifier gain and phase as a function of V supply and input power.
The following shows a captured PA surface, with an ISO gain Shaping Table overlaid.
ET Surface Analyser

• Once we have the surface of a PA we can perform the following steps:
  • Extract and manipulate Shaping Tables
  • Predict system performance
  • Compare predicted and actual performance
• Using the combination of ET Surface Explorer and ET Surface analyser we can characterise new PA in hours, not days.
ET Surface Analyser - Plots

- This tool enables you to visualise the behaviour of the PA under test:

  - Supply Impedance
  - Instantaneous Efficiency
  - Phase Surface
  - Gain Surface
Benefits of Envelope Tracking

- Fixed drain mode
- ET Mode
  - Improved battery life ~30%
  - Simplified cooling Requirements
Benefits of Envelope Tracking

- The -30% saving in battery power is dependant on signal statistics
Benefits of Envelope Tracking

- ET Surface Analyser results analysis:
  - Red predicted
  - Blue measured

- Higher device peak power
  - Larger RF cells

- More linear output without digital pre-distortion for handset applications

Fixed Drain

Envelope Tracking

Higher Output Power

Improved ACP
ETIC VALIDATION TOOLS
ETIC – Block Level Validation

• The block level test framework gives ETIC designers easy control of the following:
  • ETIC MIPI Interface
  • Envelope signal (FDP)
  • Spectrum analyser
  • Scanning DMM x40 channels
  • Oscilloscope x4 channels
  • Power Supplies x6
  • Temperature chamber
  • Temperature Sensors
  • I²C EEPROM calibration data

• Block tests can be combined to allow volumetric testing over temperature and other operating parameters
ETIC – Block Level Validation

• Test limits are derived from the device simulations are saved with the results to enable easier analysis:

<table>
<thead>
<tr>
<th>Result.iTestA473</th>
<th>errampA_stg2, 1/40 mirror of pmos output device current</th>
<th>91.70</th>
<th>119.00</th>
<th>146.30 µA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Result.iTestB473</td>
<td>errampA_stg2, 1/40 mirror of nmos output device current</td>
<td>86.50</td>
<td>116.80</td>
<td>147.10 µA</td>
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<tr>
<td>Result.iTestA474-1</td>
<td>errampA_opstage, mirror of ab_bias setting current</td>
<td>11.34</td>
<td>12.42</td>
<td>13.50 µA</td>
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<tr>
<td>Result.iTestA474-2</td>
<td>errampA_opstage, mirror of ab_bias setting current</td>
<td>22.97</td>
<td>24.65</td>
<td>26.33 µA</td>
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<tr>
<td>Result.iTestA474-3</td>
<td>errampA_opstage, mirror of ab_bias setting current</td>
<td>34.45</td>
<td>36.79</td>
<td>39.13 µA</td>
</tr>
</tbody>
</table>

• A generic GUI enables access to the ~150 different block test results.
FLEXIBLE DEVELOPMENT PLATFORM DEVELOPMENT
Flexible Development Platform - Requirements

• We have developed custom ET test equipment that has the following key features:
  • Outputs:
    • RF Frequency from 0.6 to 2.7 GHz
    • RF Sample rate 245 MSPS
    • 10 millisecond playback memory
    • Modulator control
  • Inputs
    • Dual wideband receivers 0.6 to 2.7 GHz
    • RX Sample rate 491 MSPS
  • Algorithms
    • ET Generation Interface (EGI)
    • Digital Pre-Distortion (DPD)
    • Dynamic QMC Correction
    • Automatic power level control
Flexible Development Platform – Design Flow

• We have followed the development flow show below for the Baseband firmware.
• Currently we use manual methods to translate MATLAB into FPGA and embedded ‘C’ code. But have evaluated automating the process using the ‘C’ generation tools.
• The FPGA code and fixed point models are provided to customers, so they can integrate our IP into their solutions.

### Phase#1 Modelling
- Application [MATLAB]
- Algorithms [MATLAB]
- Baseband Configuration [MATLAB]
- USB Driver [Mex32/64]

### Phase#2 Development
- Application [MATLAB]
- Algorithms [MATLAB Fixed Point]
- Baseband Configuration [DSP ‘C’]
- USB Driver [Mex32/64]

### Phase#3 Product
- Application [MATLAB]
- Algorithms [DSP ‘C’/FPGA]
- Baseband Configuration [DSP ‘C’]
- USB Driver [Mex32/64]

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FDP Design Flow
Flexible Development Platform - Validation

- We were worried that small data sets may not fully verify some of the algorithms.
- So we structured the code so could run all three versions in parallel.
- This allowed verification over long time periods and operating conditions.
Flexible Development Platform - Manufacturing

- The Flexible Development Platform is a complex piece of test equipment with 28 ports that need production test and calibration.
- We have used a programmable RF switch array to enable the automated testing of complete unit from MATLAB.
- This includes calibrating TX and RX RF attenuators at 60 different RF frequencies.

RF Switch Test Matrix
Summary – Software Integration

• We have used the following 3rd party integrations in our developments

• **32/64-bit MEX Functions**
  • Optimised ‘C’ functions

• **3rd Party DLL loading**
  • Aardvark I²C/SPI controller
  • Pico Temperature Sensors
  • Flexible Development System Driver

• **3rd Application Execution**
  • Microsoft Visual Studio – DLL compiler
  • InnoSetup - Windows installer builder

• **File Access**
  • XML Files
  • Excel Files

• **Java/C# Libraries**
  • Encryption Tools
  • Database Access

• **MATLAB Com Interface**
  • FDS control from C# & Labview
Summary – MathWorks Tools

- We have used MATLAB tools throughout our development process from system modelling to device validation
- We have used the following MATLAB products at each stage:

  • **System Modelling**
    - Simulink
    - Signal Processing Toolbox
    - Communication Systems Toolbox
    - DSP System Toolbox
    - RF Toolbox

  • **Code Generation**
    - Fixed Point Designer
    - MATLAB Coder

  • **RF Testing**
    - Instrument Control Toolbox

  • **ETIC Testing**
    - Instrument Control Toolbox

  • **Customer Releases**
    - MATLAB Compiler
    - MATLAB Builder NE

- It could be said that “MATLAB is the glue that holds it all together”
THANK YOU