Non-Linear RF Research and Educational Laboratory

PI: Patrick Roblin    (MISES, SSEP)
CoPI: Roberto Rojas   (ESL)
CoPI: Mohammed Ismail (MISES)
CoPI: Len Brillson    (SSEP)
CoPI: Wu Lu           (SSEP)
CoPI: Lee Potter      (IPS)
CoPI: Oscar Takeshita (IPS)

Department of Electrical Engineering
The Ohio State University

Agency:
Air Force Office of Scientific Research
Dr. Witt
• Overview of DURIP equipment proposal - Patrick Roblin
  - DURIP team
  - DURIP equipment requested
  - Need for equipment and examples of applications

• Impact of Equipment: from systems, to devices, to materials (a top down approach)
  - Signal processing research - Lee Potter
  - Wireless testbed - Oscar Takeshita:
  - RFIC design - Mohammed Ismail
  - Mixed signals & UWB radar-on-chip - Steve Bibyk
  - Phase array antenna - Roberto Rojas
  - Projects relevant to non-linear RF - John Volakis
  - Designing GaN devices - Wu Lu
  - Defects and traps in GaN material/devices - Len Brillson
  - Electronic traps in III-Nitride - Steve Ringel
Non-Linear RF DURIP Team

- Antenna Electromagnetism (ESL)
- Communication Signal Processing (IPS)
- Materials and Devices (SSEP)
- Microwave, RFIC Mixed Signals (MISES)

<table>
<thead>
<tr>
<th>Group</th>
<th>Full Name</th>
<th>Number of Faculty Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESL</td>
<td>ElectroScience Laboratory</td>
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<tr>
<td>IPS</td>
<td>Information Processing System Lab</td>
<td>8</td>
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<tr>
<td>MISES</td>
<td>Mixed Signal Electronic Laboratory</td>
<td>4</td>
</tr>
<tr>
<td>SSEP</td>
<td>Solid State Electronics and Photonics</td>
<td>8</td>
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EE Department committed release time for center development.
Equipment Requested

Thermal Modeling

Infrared Camera
Probe Station

DUT

Pulsed–IV
Pulsed–RF

LSNA

Non–linear RF
Behavioral
System Models

Non–linear RF
Isothermal
Device Models

Isothermal
Device Models

MISES/SSEP Microwave Laboratory
The Ohio State University
## DURIP Equipment Budget

<table>
<thead>
<tr>
<th>Equipment:</th>
<th>Source</th>
<th>Cost</th>
<th>Revised Cost</th>
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<tbody>
<tr>
<td>Large-signal network analyzer:</td>
<td>Agilent</td>
<td>$367,246</td>
<td>$300,000</td>
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<tr>
<td>Pulsed RF system:</td>
<td>Agilent</td>
<td>$506,025</td>
<td>$358,000</td>
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<td>Infrared &amp; Cascade probe station:</td>
<td>Cascade &amp; Indigo</td>
<td>$156,530</td>
<td>$50,000</td>
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<tr>
<td><strong>Total Equipment</strong></td>
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<td><strong>$1,029,801</strong></td>
<td><strong>$708,000</strong></td>
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<td>OSU cost-share</td>
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<td><strong>$514,878</strong></td>
<td><strong>$354,000</strong></td>
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<tr>
<td>Requested DoD share</td>
<td></td>
<td><strong>$514,923</strong></td>
<td><strong>$354,000</strong></td>
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</tbody>
</table>
13 LSNAs are in use around the world now.

<table>
<thead>
<tr>
<th>Country</th>
<th>Institution</th>
<th>Number of LSNA</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>Agilent (demo, design, modeling)</td>
<td>3 LSNA</td>
</tr>
<tr>
<td></td>
<td>NIST</td>
<td>1 LSNA</td>
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<tr>
<td>Belgium</td>
<td>Katholieke Universiteit Leuven, Dept. TELEMIC</td>
<td>1 LSNA</td>
</tr>
<tr>
<td></td>
<td>Vrije Universiteit Brussel, Dept. Electrical Eng.</td>
<td>1 LSNA</td>
</tr>
<tr>
<td></td>
<td>Agilent-Europe</td>
<td>3 LSNAs</td>
</tr>
<tr>
<td>France</td>
<td>IRCOM - Universite de Limoges</td>
<td>2 LSNAs* + 1 pulsed-RF</td>
</tr>
<tr>
<td>Ireland</td>
<td>National Micro-Electronics Research centre</td>
<td>1 LSNA</td>
</tr>
<tr>
<td>Singapore</td>
<td>National University of Singapore</td>
<td>1 LSNA</td>
</tr>
</tbody>
</table>

* IRCOM has just acquired a second LSNA dedicated to system measurement. Their first LSNA is dedicated to non-linear pulsed-RF measurement.
Continuous push for:

- Higher frequencies of operation
- Wide and ultra-wide bandwith communication and radar systems
- Highly linear electronics to conserve spectrum resource
- High power handling (base-station, satellite)
- Efficiency (talk time, satellite, linearization)
- New modulation and code techniques (constant envelope, vector modulation)
Non-linearities in RF Systems

Non-linearities arise from the complex dependence of the device current sources (IVs) and charges (QVs) upon their state-variables such as terminal voltages, traps state, internal device temperature $T_{dev}$, body voltages $V_b$ and so on.

Non-linearities lead to intermodulation and spectral regrowth.

Spectral regrowth depends on the 3rd and 5th derivatives of the current sources and charges!
Need for Higher Derivatives in Behavioral Modeling

The LSNA provides the required phase and amplitude of the in-band intermodulation products to account for the higher derivatives.
Need for Higher Derivatives in Device Modeling

(a): Absence of higher derivatives leads to a 10 dB error in IMD.
(b) Using 3rd order derivative continuity gives a closer prediction of the IMD.
The LSNA will provide the missing higher order derivatives.
Large Signal Network Analyzer

Building blocks:
(1) test-set
(2) down-converter
(3) data acquisition
(4) CW source or modulation source

Characteristics:
RF bandwidth: 0.6 to 20 GHz
max RF power: 10 Watt
Modulation bandwidth: 8 MHz
Modulation: must be periodic
Measurement Examples

CW in frequency domain  
\( a_1, b_1, a_2, b_2 \) (FET @ 2.4 GHz)

CW in time domain  
\( v_1, i_1, v_2, i_2 \) (FET @ 2.4 GHz)
Modulation

Time Domain

 Frequency Domain

$3^{rd}$ harmonic envelope

Fundamental envelope

Spectral regrowth
**What is large-signal analysis?**

S-parameters are commonly used to describe small signal device behavior. They are extremely valuable as they offer a mathematical representation of linear device behavior. The application of S-parameters allows circuit designers and modelers to achieve excellent correlation between simulation and measurement. However, S-parameters only apply to linear devices and systems, where the superposition principle is valid. Large-signal environments usually push devices into their nonlinear operating regions, and S-parameters and the superposition principle no longer apply.

Researchers and design engineers face a significant problem when trying to translate high-level system specifications such as spectral regrowth, adjacent-channel-power-ratio (ACPR) and third-order-intercept (IP3) into concrete device and process parameters. There is an urgent need for a framework which deals with large-signal behavior from device to system level in a coherent way, that can be applied to measurements, modeling and simulation. Imagine the increase of productivity in the design flow, if process engineers could work with circuit designers and system level engineers based on the same measurement tools and methods.

A long-term cooperative effort between Agilent and several research institutions is under way with the goal of developing a new analysis framework for large-signal RF and microwave design process. With its strong presence in measurement, modeling and simulation, Agilent is uniquely positioned to lead this effort. Agilent’s large-signal network analyzer has allowed participating researchers to gain new insight into their device’s behavior under large signal conditions. Now, for the first time, this measurement system is being made available to Agilent’s customers.

Voltage and current relationships are the fundamental information used by computer-aided engineering (CAE) tools and device-level models. What has been missing is a way to accurately measure voltages and currents at the device under test’s (DUT’s) ports under realistic stimulus and load conditions. The large-signal network analyzer takes a first step towards bridging the gap between measurement, modeling and simulation, from device level to system level.
The concept of dynamic loadline is very useful for microwave power amplifier designers. The dynamic loadline represents current versus voltage at the output of a transistor for the fundamental and harmonics, under given bias conditions and input and output match. Once the dynamic loadline is determined, the designer can easily tune bias parameters, input power and output impedance to optimize output power or power-added efficiency (PAE). Up to now, dynamic loadline information was only available from advanced simulators, and depended therefore on the accuracy of the large-signal models of the device. The large-signal network analyzer makes it possible for the first time to accurately measure the dynamic loadline directly, without the dependence on accurate models. This allows faster and more efficient design cycles.

A GaAs HEMT is shown in voltage and current time domain view, as well as in voltage – current state space and frequency domain.

For additional application information and technical papers about Large-Signal Network Analysis, please go to [http://www.agilent.com/find/lsna](http://www.agilent.com/find/lsna)
Memory Effects

Memory effects are low-frequency dispersion effects (DC to MHz) associated with various physical effects:

- Deep level traps (GaN, SiC)
- Self-heating (thermal distributed network) (HBT, LDMOSFET, SOI-MOSFET)
- Parasitics bipolar transistor & impact ionization (SOI-MOSFET, HEMT)

Because they respond to the RF modulation envelope (DC-MHz), memory effects are hampering the development of wide-bandwidth modulation (WCDMA, UWB radar).

- They introduce time-varying non-linearities leading to further performance degradation.
- Present linearization schemes used in power amplifiers are not effective for wide-bandwidth modulation due to memory effects.
- Present device models are not capable of accurately accounting for non-linearities and memory effects, limiting their usefulness in circuit design.
Modeling of Memory Effects in Devices

- Intrinsic FET

- Both analytic and table (B-spline) representations can be used

- Models parameters extracted from pulsed-IV and pulsed-RF measurements

- Models implemented in ADS
Parasitic Bipolar Effect in SOI-MOSFET

Circle: Iso-thermal DC-IV, Plain line: Pulsed-IV.
Both plots are isothermal! Traps and parasitic bipolar-transistor remain frozen in pulsed-IV measurements but not in isothermal DC-IV.
Self-Heating in a LDMOSFET

Electro-thermal DC IV characteristics $T_{sub} = 60^\circ$C.

The device surface temperature $T_{dev}$ is indicated.
Pulsed-IV Measurements

Pulsed-I-V Characteristics for $V_{GS}=4.75 \, V$ and $V_{DS}=13.7 \, V$ and $T_{Sub}=35 \, ^{\circ}C$

Pulsed-IVs showing the starting bias point
Repetition rate 10 kHz, Pulsed duration $1\mu s$, Duty rate: 1% Pulsed-IV have a double bias dependence!

Pulsed-IVs from 45 to 105 °C

MISES/SSEP Microwave Laboratory
Pulsed RF system

- OSU system (same principle as IRCOM’s system, but 2-6 GHz)
- Agilent Pulsed RF system (2-20 GHz) (dedicated system, high-performance)
- Agilent LSNA can be used for doing pulsed RF (same dynamic range but slower). LSNA acquires non-linear pulse response as well.
The first sample point during the second pulse (B) should be at the phase of the first point outside (A), in order to obtain an array of samples suitable for FFT.

Consequences:

- the LSNA calibration procedure from Agilent NMDG is suitable,
- $AdcF$, $Fo$, $sF$, and $To$ parameters are not independent,
- The $AdcF$ clock must be phase-locked with RF synthesizer 10 MHz to avoid a large phase shift between A-1 and B point.
Need for Infrared Thermal Imaging of Transistors

Modeling of distributed thermal effects in FETs

Image method is applied to a 140mm 7 finger FET
Lateral Temperature Distribution Across the FET

Temperature Distribution of a Simulated 140mm LDMOSFET

10 °C drop for a 70 °C rise.
Fig. 2 Image magnification sequence, from left to right, 1/5X, 1X, 5X and 25X, including visible overlay.

Fig. 3 Quadrant display showing unpowered radiance image (upper left), powered radiance image (upper right), emissivity matrix (lower left) and “true temperature” thermogram (lower right).

Fig. 4 Typical InfraScope II screen display illustrating line scan and statistical display (upper left).

Fig. 5 Navigation image showing superposition of thermal information (color) over visible image (black and white).
Need for Higher-Order Distributed Thermal Network

Transient and steady-state responses of the device average temperature.

(A) Transient response of device temperature in (K) over time in (Sec).

(B) Steady-state response of device temperature in (K).

A single RC thermal model is sufficient for DC and RF but NOT for modulated RF.
Example of Linearization Accounting for Thermal Memory

IQ Modulator

T (I, T_{dev})

Q(I, T_{dev})

PA

P_{inst}

T_{sub}

Low pass Filter

Square-law detector

P_{bb}

P_{bb}

RF predistortion System

The real device temperature $T_{dev}$ is estimated and used to update the temperature dependent linearization while accounting for memory effect.
Applications of DURIP equipment

The DURIP equipment requested will permit to

- qualify device/system linearity for wide-bandwidth system applications * (LSNA: Lu, Takeshita)
- measure time constants associated with memory effects* (Pulsed RF: Brillson, Ringel, SSEP)
- develop DC to RF device models accounting for memory effects (Pulsed RF: Lu, Roblin)
- develop device models accurately accounting for non-linearities (LSNA+pulsed RF, Roblin)
- develop and test improved amplifier linearization schemes accounting for memory effects (LSNA: Serrani, MISES, IPS)
- develop and test improved non-linear system models (LSNA: IPS, MISES)
- develop and test non-linear RFIC (LSNA: Ismail, Rojas, Volakis)
- improved DAQ and RF signal processing (LSNA: Bibyk, Potter )
- test impact of non-linearities on wide-bandwidth modulation (LSNA: Takeshita, IPS)

* Application to GaN devices: Correlate memory effect observed in RF circuits with traps and defects independently identified in our SSEP labs (Brillson, Ringel) for improved material growth (Ringel) and device fabrication (Lu).
Presentation

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