Novel Techniques of RF High Power Measurement

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Why is RF High Power Measurement is Important?

- Semiconductor and flat panel industry requires RF Power level up to 50kW with better than 1% power accuracy, for frequencies 1-200MHz
  - Process control
  - Repeatability
  - Faster diagnostics
  - Increased yield
  - Reduced development time
- Existing RF power methods are typically 1-3% accurate into real impedance (50 Ohms)
  - Accuracy is decreasing with VSWR
- We lack a national (e.g. NIST) or international RF high power standard
  - RF high power calibration is performed using only indirect methods
RF High Power Measurement

Topics

- Background on RF High Power Measurement
- New Solutions for Real Impedance Lines and Loads
  - Double diode detector with digital correction
  - Multiplier with digital correction
- New Solutions for Complex Impedance Lines and Loads
  - Direct digital sampling
- Calibration Methods
- Summary and Future work
Real Impedance RF High Power Measurement Application

Advantages:
- Cost effective

Disadvantages:
- Limited plasma process information
- Error of existing power measurement methods is 1%-3%
- Proposed methods have 3X better accuracy

Impedance of the line is fixed
\[ Z = 50 + j0 \]
\[ \tan(\phi) = 0 \]
Complex Impedance RF High Power Measurement Application

Advantages:
- Better plasma process control
- Feedback diagnostics

Disadvantages:
- Expensive

Error of existing methods for power measurement is >1% and >1.5% for impedance measurements
New method has 3X better accuracy for power and impedance
High Power RF Power Measurement - Origin of Errors

There are 4 categories of errors in RF power measurement:

- RF level linearity (Power/Impedance vs. RF Signal Level)
- Frequency error (Power/Impedance vs. Frequency)
- VSWR error (Power/Impedance vs. VSWR)
- Environmental Stability (Accuracy vs. Humidity and Temperature)

All above errors compound into the total error of the RF measurement method.

The RF components have parasitic characteristics and stability issues, therefore any accurate RF measurement requires either “ideal components” or a proper correction (analog and/or digital).
Anatomy of the typical RF High Power Measurement

Advantages:
- Mature technology

Disadvantages:
- Less Accurate. Accuracy is best into 50Ohm and is degrading with VSWR
  - Power Error >1%
  - Impedance Error >1.5%
- Complex
- Accuracy is changing with temperature and humidity

Typical RF High Power Instrument is analog while the new technique is digital …
Proposed Enhanced Digital RF Measurement Method

Advantages:
- Better Accuracy
  - Power Error $\approx 0.3\%$
  - Impedance Error $\approx 0.3\%$
- Smaller size ($\approx 50\%$)
- Extra features
  - Frequency agile (2-64Mhz)
  - Plasma process feedback
- Environmentally stable

Disadvantages:
- Cost of Development
RF Measurement Method for Real Impedances – Background

\[ P_{\text{load}} = V \cdot I \cdot \cos(\phi) \]

For Real Impedance Loads and Lines \( \cos(\phi) = 1 \) therefore Power Measurement is simplified to V\text{rms} measurement:

\[ P_{\text{load}} = \frac{V_{\text{rms}}^2}{Z_0} \]

or I\text{rms} measurement:

\[ P_{\text{load}} = \frac{Z_0 \cdot I_{\text{rms}}^2}{Z_0} \]

However, on RF we use Forward and Reflected Power as follows:

\[ P_{\text{load}} = P_{\text{fwd}} - P_{\text{rfl}} \]

with the following equations:

\[ P_{\text{fwd}} = \frac{V_{\text{fwd}}^2}{Z_0} \]
\[ P_{\text{rfl}} = \frac{V_{\text{rfl}}^2}{Z_0} \]

Error of existing power measurement methods is 1%-3%

Proposed methods have 3X better accuracy
Illustrative RF Peak Diode Detector Circuit

Advantages:
- Simple
- Wide-band

Disadvantages
- Non-linear
- Does not work at low level signals

Historically the most basic design for RF voltage measurement
Improved Double Diode Detector Circuit

Advantages:
- Simple
- Wide-band
- Works at low level signals

Disadvantages
- Non-linear at high signal level
Calculations Required for Calibrating a Double Diode Detector

Drawback:

RF Power calculation requires a second degree polynomial correction

Analog multiplier solution is simple to correct digitally…
Advantage:

Multipler will provide the voltage squared

RF Power measurement is linear and requires only scaling and offset correction

Besides power scaling there are further correction requirements…
**$P_{RF}$ Measurements—Other Correction Requirements:** Thermal and Bandwidth

**Temperature Stability Requirement:**
- Tests done in an environmental Chamber confirmed drift of analog components

**Wideband Requirement:**
- For instrumentation with passive input filters, a correction of amplitude with frequency is mandatory

Both requirements along with RF Power correction can be solved by DSP…
Illustrative Digital Correction

Digital Correction will enable:
- Correction of measurement with temperature
- Correction of measurement with frequency bandwidth
- Correction of measurement with amplitude of input signal

Other Digital Functions:
- Serial communications
- Averaging of the signal

All the digital corrections are improving the RF Power accuracy …
Experimental Error Analysis for Multiplier and Double Diode Detector

<table>
<thead>
<tr>
<th>Standard (W)</th>
<th>Vout (V)</th>
<th>Offset (V)</th>
<th>Slope (W/V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>0.962</td>
<td>0.030</td>
<td>644.21</td>
</tr>
<tr>
<td>1122</td>
<td>1.828</td>
<td>0.030</td>
<td>624.46</td>
</tr>
<tr>
<td>2995</td>
<td>4.94</td>
<td>0.030</td>
<td>610.19</td>
</tr>
</tbody>
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</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>2.194</td>
<td>0.781</td>
<td>300.59</td>
</tr>
<tr>
<td>1122</td>
<td>2.807</td>
<td>0.781</td>
<td>273.47</td>
</tr>
<tr>
<td>2995</td>
<td>4.268</td>
<td>0.781</td>
<td>246.38</td>
</tr>
</tbody>
</table>

Analog Multiplier results
RF Power equation:
\[ x = \frac{A}{D}\text{_reading} \]
\[ P = Offset + x \times Slope \]
Offset = 21.284W
Slope = 602.15 W/V
Max Error = 0.05%

Double Diode Rectifier results
RF Power equation:
\[ P = A \times x^2 + B \times x + Offset \]
Offset = 7.293W
A = 207.33
B = -184.66
Max Error = 0.22%
Accuracy Results for the Analog Multiplier with Digital Correction

Calibration results over six devices that employed a multiplier with a digital correction delivered:

- RF Power Error < 0.20% for 30-3000W signal level
- RF Power Error < 0.30% within 15°C-45°C

Results were compared to a Reference Standard calibrated on a calorimeter

In conclusion …
Two improved methods were developed for RF high power measurement:

1) Double diode detector technique with digital correction
2) Multiplier technique with digital correction

Both designs employ a digital correction for frequency bandwidth and temperature variations.

Both designs achieved a power error $< 0.3\%$ versus the existing state of the art that has a typical error $1-3\%$.

Far more challenging are RF measurements into complex impedances …
RF Measurement for Complex Impedances – Basics

\[ P_{\text{load}} = V \cdot I \cdot \cos(\phi) \]

For measurements into complex impedance loads and lines the most difficult element to measure (and major source of errors) is: \( \cos(\phi) \)

Advantages:
- Better plasma process control
- Feedback diagnostics

Disadvantages:
- Expensive
New Method for Measuring Complex Impedances

Advantages:
- Better Accuracy
  - Power Error $\approx 0.3\%$
  - Impedance Error $\approx 0.3\%$
- Smaller size ($\approx 50\%$)
- Extra features
  - Frequency agile (2-64Mhz)
  - Plasma process feedback
- Environmentally stable

Disadvantages:
- Cost of development
New Method for Measuring Complex Impedances—Direct Digital Sampling

Analog circuit topology consists of:
- Balun Transformer
- Low pass filter

Forward and reflected channels are similar and parallel sampled
Direct Digital Sampling
Digital Signal Processing Schematic

Sampling freq. $f_c$
Window freq. $f_w$

Input signal frequency $f_s$

Correction Matrix (4x4)

$V_f^2 = V_{f-Q_c}^2 + V_{f-I_c}^2$

Sampling
Hann Window
Fourier Transform
Calibration
RF Calculus
Direct Digital Sampling
Amplitude and Phase Processing I

We know the frequency $f_s$

$$V_f = A \sin(\omega_s t + \varphi_f)$$

Digital Sampling

$$V_{fi} = A \sin(\omega_s t_i + \varphi_f)$$

* $\sin(\omega_s t_i)$
* $\cos(\omega_s t_i)$

Both I and Q components are summed over the observation window ...
Direct Digital Sampling
Amplitude and Phase Processing II

\[
V_{f-I} = \frac{1}{N} \sum_{i=0}^{N-1} V_{f-I_i}
\]
\[
V_{f-Q} = \frac{1}{N} \sum_{i=0}^{N-1} V_{f-Q_i}
\]

\[
V_{f-I_i} = 0.5A[\cos \varphi_f - \cos(2\omega_s t_i + \varphi_f)]
\]
\[
V_{f-Q_i} = 0.5A[\sin \varphi_f + \sin(2\omega_s t_i + \varphi_f)]
\]

After DFT we still have the signal amplitude and phase information:

\[
\begin{align*}
V_{f-I} &= \frac{A}{2N} \sum_{i=0}^{N-1} \cos \varphi_f + \frac{A}{2N} \sum_{i=0}^{N-1} \cos(2\omega_s t_i + \varphi_f) \\
V_{f-Q} &= \frac{A}{2N} \sum_{i=0}^{N-1} \sin \varphi_f + \frac{A}{2N} \sum_{i=0}^{N-1} \sin(2\omega_s t_i + \varphi_f)
\end{align*}
\]

These Sum Terms are Zero because:

a) Observation Period is large compared to the RF signal frequency: \( f_w \ll f_s \)
N is the number of samples acquired during the Hann Window
b) Hann function is going to attenuate the beginning and end discontinuities …

Next, both I and Q components are corrected by a calibration matrix …
In this example the Hann window has 1µSec period, the input signal has 13.56MHz and the sampling rate is 100Ms/Sec.

The Hann window effect can be described by the equation:

$$w(i) = 0.5 \left\{ 1 - \cos\left(\frac{2\pi i}{N}\right) \right\}$$

where:
- $i = 0, 1, ..., N$
Four Channel Digital Calculation of Correction for Direct Digital Sampling

\[ \begin{bmatrix} V_{f-Ic} \\ V_{f-Qc} \\ V_{r-Ic} \\ V_{r-Qc} \end{bmatrix} = K \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} V_{f-I} \\ V_{f-Q} \\ V_{r-I} \\ V_{r-Q} \end{bmatrix} \]

\[ K \text{ is a scaling factor for amplitude, does not affect phase} \]

\[ \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

aij i,j=1 to 4 are calibration factors for phase correction

In ideal case (no phase distortion)
the correction is the identity matrix

Corrected values for I and Q will provide \( V_f, V_r \) and \( \phi \)...
Digitally Corrected Amplitude and Phase for Direct Digital Sampling

The corrected values for I and Q are providing real readings of the input signal

\[ V_f^2 = V_f - Q_c^2 + V_f - I_c^2 \]
\[ V_r^2 = V_r - Q_c^2 + V_r - I_c^2 \]

\[ \phi_{fc} = \tan^{-1} \left( \frac{V_{fc} - Q}{V_{fc} - I} \right) \]
\[ \phi_{rc} = \tan^{-1} \left( \frac{V_{rc} - Q}{V_{rc} - I} \right) \]

\[ \phi = \phi_{fc} - \phi_{rc} \]
Determination of Calibration Matrix for Complex Impedance Measurements I

If we know the Matrix $Y$ and the Matrix $X$ (as reported by the RF Measurement) in at least 16 cases then we can calculate calibration Matrix $A$.

How to determine the 16 elements of matrix $A$...
Determination of Calibration Matrix for Complex Impedance Measurements II

DUT reports Matrix X for every single load.

The RF match is calibrated (known impedance) into 113 loads.

Changing the settings of the Variable Match to 113 different loads will generate 113 equations:

\[
[Y] = K \cdot [A] \cdot [X]
\]

Determining Calibration Matrix A reduces to solving an over-specified system with 113 equations and 16 unknowns.

We know the RF signal phase (from the load) and we measure the RF Power, therefore we know Matrix Y.

We Measure the Power Level.
Test Results for Direct Digital Sampling into Complex Impedances

1) Impedance Error <1% for loads up to VSWR=5

2) 6 different DUT’s had an Error<0.1% into a fixed load Z=17+j2.7

Red dot = Target impedance, measured with an Impedance Analyzer
Green Circle = Impedance Measured by the new measurement system

Test bench setup
Direct Digital Sampling. Power Measurements Test Results in 50Ω

Power Error < 0.71W compared to a calibrated Reference Standard

Power Error < 0.34%* compared to a calibrated Reference Standard

* 0.15% out of the Power Error was identified as systemic calibration issue related to the match losses measurements

<table>
<thead>
<tr>
<th>RF Power (W)</th>
<th>DUT Power (W)</th>
<th>Reference Standard Power (W)</th>
<th>Error</th>
<th>UM</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>31.37</td>
<td>32.08</td>
<td>-0.71 W</td>
<td>W</td>
</tr>
<tr>
<td>50</td>
<td>49.56</td>
<td>50.07</td>
<td>-0.51 W</td>
<td>W</td>
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<td>199.91</td>
<td>-0.24 W</td>
<td>W</td>
</tr>
<tr>
<td>400</td>
<td>399.48</td>
<td>399.88</td>
<td>-0.10 %</td>
<td>%</td>
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<tr>
<td>800</td>
<td>798.82</td>
<td>800.34</td>
<td>-0.19 %</td>
<td>%</td>
</tr>
<tr>
<td>1000</td>
<td>997.71</td>
<td>1000.98</td>
<td>-0.33 %</td>
<td>%</td>
</tr>
<tr>
<td>1500</td>
<td>1499.47</td>
<td>1501.36</td>
<td>-0.13 %</td>
<td>%</td>
</tr>
<tr>
<td>2000</td>
<td>1999.83</td>
<td>2001.34</td>
<td>-0.08 %</td>
<td>%</td>
</tr>
<tr>
<td>2500</td>
<td>2501.55</td>
<td>2500.45</td>
<td>0.04 %</td>
<td>%</td>
</tr>
<tr>
<td>3000</td>
<td>2984.4</td>
<td>2994.45</td>
<td>-0.34 %</td>
<td>%</td>
</tr>
</tbody>
</table>
Direct Digital Sampling
Conclusions

New RF High Power Measurement Technique with:

- Better Accuracy
  - Power Error \(\approx 0.3\%\) vs. typical 1\% of existing methods
  - Impedance Error \(\approx 0.3\%\) vs. typical 1.5\% of existing methods
  - Accuracy is consistent over large VSWR
- Smaller size (\(\approx 50\%\))
- Extra features
  - Frequency agile (2-64Mhz)
  - Plasma process feedback
- Environmentally stable

An accurate measurement method should be complemented by a good reference …
Calibration Techniques for High Power RF. Overview

RF Power High Power (>100W) does not have a NIST, nor any other International Standard

There are only Indirect Methods to calibrate RF Power Instruments, typically using substitution methods

In RF, Voltage level is not a good method of Power Measurement

\[ P = V \times I \times \cos(\varphi) \]
Calibration Techniques for High Power RF. Wet Calorimeter

Wet Calorimeter compares the temperature increase in the same load by an RF source and a DC source. When the temperatures are equal we conclude that the DC powers is equal to RF delivered power.

#1 Error: \( \Delta T = T_{out} - T_{in} \) measurement

#2 Error: \( I_{DC} \) measurement

When the temperatures are equal we conclude that the DC powers is equal to RF delivered power.
Calibration Techniques for High Power RF. New Technique using Dry Calorimeter I

Dry Calorimeter compares the RF power level between two instruments, one as a reference and the other one unknown, using a calibrated Directional Coupler.

\[ K = 10 \times \log \left( \frac{P_3}{P_2} \right) \]

A 20dB coupler would have 100:1 Power Ratio (K=100)

Directional Coupler with a calibrated power coupling coefficient, K
Novel Techniques of RF High Power Measurement. Summary

It is more practical to employ the proper digital correction technique than to research ideal components.

1) Two Improved Techniques of Power Measurement for Real Impedances were presented
   - Multiplier followed by digital correction (3X accuracy improvement)
   - Double diode detector followed by digital correction

2) A New RF Measurement Technique for Complex Impedances was presented
   - Direct digital sampling (3X improvement)
   - A new calibration method for complex impedance instruments

Results on all the above methods have lower errors than all previous methods

3) Research results into RF high power calibration methods
   - Wet Calorimeter Error Analysis
   - New Dry Calorimeter Method
Novel Techniques of RF High Power Measurement. Future Work

It is impractical to calibrate all RF instruments on the RF calorimeter; transfer standards are employed.

1) Reduce calibration time on the RF calorimeter by using extrapolation techniques.

RF Calorimeter can improve the absolute accuracy of the measurement.
Novel Techniques of RF High Power Measurement. Future Work

It is impractical to calibrate all RF Instruments on the RF Calorimeter; Transfer Standards are employed.

1) Reduce calibration time on the RF Calorimeter by using extrapolation techniques.

2) Increase reliability and the RF Power limit on the RF Calorimeter. In this moment maximum RF calibrated power is 3500W.

3) Research the limitations of the Direct Digital Sampling Method.
Novel Techniques of RF High Power Measurement

Questions?