60 GHz Power Amplifier Design for Wireless HDMI (WPAN)

Agilent EEs of EDA
Innovative Solutions,
Breakthrough Results

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Innovative Technology,
Experience, Support

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FSD Design & Applications
Objectives

Demonstrate Complete MMIC ADS Desktop Design Flow

- ADS Desktop DRC
- ADS Desktop LVS

Showcase performance of TriQuint’s TQP13 foundry process

- Process Statistics
- PDK, with MMIC Layout Toolbar
Complete Flow Overview For ADS 2009 Update 1

MMIC Overview

The MMIC ADS Desktop Flow provides the industry's strongest, most complete set of MMIC design tools available in one environment:

- Integrated multi-solver electro-magnetic technology to help deal with the challenge of increasing complexity
- A foundry-endorsed design environment to help streamline the foundry submission process
- Full manufacturing layout tightly integrated with schematic
- The convenience of a DRC and LVS tool on every MMIC designer's desktop

http://www.agilent.com/find/eesof-mmic-overview
Complete MMIC ADS Desktop Flow
Presentation Topics

• Specifications
• Process Selection
• Device Stability
• Device Matching
• Initial Linear Simulations
• Non-Linear Simulations
• EM Simulations
• WPAN Standard Simulations
WPAN Specification

WPAN is defined in IEEE P802.15.3c/D08, "Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs): Amendment 2: Millimeter-wave based Alternative Physical Layer Extension", 2009

A personal operating space is a space about a person or object that typically extends up to 10m in all directions and envelops the person whether stationary or in motion.

It’s used to convey information over relatively short distances among a relatively few participants. Unlike WLAN, connections effected via WPAN involve little or no infrastructure. This allows small, power efficient, inexpensive solutions to be implemented for a wide range of devices.
Application

Supports streaming uncompressed audio and video at up to 1080p resolution, 24 bit color at 60 Hz refresh rates

• Delivery compressed A/V streams and data
• Unlicensed operation at 60 GHz with a typical range of at least 10 m for highest resolution HD A/V
• Smart antenna technology to enable non line of sight (NLOS) operation

Two PHY major modes, both OFDM

• High rate PHY (HRP): up to 4 Gb/s, beam formed directional link
• Low rate PHY (LRP): up to 10 Mb/s in omni-directional mode
**TQP13N Process Overview**

- 0.13um optical self aligned gate depletion pHEMT process
- Coupled with high density capacitors, epi resistors, thin film resistors (TFR), and 2 layers of gold interconnect.
- With a typical Ft of 95GHz, TQP13N is used for V-band automotive radar, and high frequency point-to-point radio applications.
- Utilizes optical lithography process in place of traditional e-beam to achieve cost efficiencies.
Start By Understanding The Design Medium

\[ \lambda = \frac{c}{f \sqrt{\varepsilon_{\text{eff}}}} \quad \text{\(\lambda\) (inches)} = \frac{11.803}{f \sqrt{\varepsilon_{\text{eff}}}} \quad \varepsilon_{\text{eff}} \approx \frac{2}{3} \varepsilon \]

\[ \lambda \text{ (inches)} \approx \frac{11.803}{60 \sqrt{2 \times 12.9}} = 67.1 \text{ mils, 1704 um} \quad \frac{\lambda}{4} (@ 60 \text{ GHz}) = 16.8 \text{ mils, 426 um} \]

Microstrip Line Reference
A Designer’s Guide To Microstrip Line
Microwaves, May 1977
I.J. Bahl & D.K. Trivedi

\[ Z_0 = \frac{60}{\sqrt{\varepsilon_{\text{eff}}}} \ln \left( \frac{8 H}{W} + 0.25 \frac{W}{H} \right) \text{ (ohms)} \]
\[ \varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ \left( 1 + 12 \left( \frac{H}{W} \right) \right)^{-\frac{1}{2}} + 0.04 \left( 1 - \left( \frac{W}{H} \right) \right)^{\frac{3}{2}} \right] \]

\[ Z_0 = \frac{120 \pi}{\sqrt{\varepsilon_{\text{eff}}} \left[ \frac{W}{H} + 1.393 + \frac{2}{3} \ln \left( \frac{W}{H} + 1.444 \right) \right]} \text{ (ohms)} \]
\[ \varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + 12 \left( \frac{H}{W} \right) \right)^{-\frac{1}{2}} \]
LineCalc Provides More Accurate Results
Understanding Device Stability

S-Parameters, Noise Figure, Gain, Stability, Circles, and Group Delay versus Frequency
Simulation Results In Preconfigured Data Display
Simulation Results In Preconfigured Data Display
Varying The Bias Voltage And Observing Device Behavior
Review Device Geometry To Better Understand How And Where Feedback Can Be Implemented
Removing One Via Has Considerable Effect On Stability

Since the device’s Source has proven to be a very sensitive area if we were to base our design on adding stability elements to this area the design would also prove sensitive or not very producible.
To get a better understanding of how to model this feedback mechanism we need to consider how it will be implemented.
Feedback Implementation

• The gate to drain feedback requires routing around one of the vias.

• The additions to ADS 2009 PDKs allows easy and quick routing.

Trace Routing Extraction Into Microstrip Elements
Feedback Based On Layout Implementation

Stability Factor, K
Geometric stability factors
mu_source and mu_load

m2
freq=60.00GHz
K=1.424
Quick Monte Carlo Check With Process Statistics Enabled
ADS Has Routines To Build Matching Networks
S-Parameter Application Note

http://contact.tm.agilent.com/Agilent/tmo/an-95-1/index.html
Using Rollett’s Stability Analysis And Conjugate Matching
With a little tuning, design was quickly centered to WPAN frequency range.
Three Stage Amplifier
Linear 3-Stage Amplifier Performance

- $m_1$ at $f_{\text{freq}}=60.10\,\text{GHz}$ with $\text{dB}(S_{21})=26.935$
- $m_2$ at $f_{\text{freq}}=60.00\,\text{GHz}$ with $S_{11}=0.004$ and $Z_0^*=(1.029 + j0.166)$
- $m_3$ at $f_{\text{freq}}=60.00\,\text{GHz}$ with $S_{22}=0.332$ and $Z_0^*=(1.335 + j0.741)$

Graphs showing frequency response over the range from 65.000GHz to 65.000GHz.
Non-Linear Amplifier Performance

![Graph showing non-linear amplifier performance with dBm(Pout) vs. Pin relationship.]

$m1$

$Pin = 10.000$

$dBm(Pout[::1]) = 12.561$
Power Sweeps/Gain/Transient Response

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**Input Power Selector**

**Output Spectrum**

**Transducer Power Gain, dB**

**Gain Compression between markers, dB**

**Output Power at Marker 2, dBm**

**Fundamental and Third Harmonic, dBm**

---

**Available Source Power (dBm)**

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Power Added Efficiency, %</th>
<th>DC Power Consumed (Watts)</th>
<th>High Supply Current (mA)</th>
<th>Thermal Dissipation (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.02</td>
<td>1.624</td>
<td>0.406</td>
<td>1.624</td>
</tr>
<tr>
<td>30</td>
<td>0.04</td>
<td>1.624</td>
<td>0.406</td>
<td>1.624</td>
</tr>
<tr>
<td>40</td>
<td>0.08</td>
<td>1.624</td>
<td>0.406</td>
<td>1.624</td>
</tr>
<tr>
<td>50</td>
<td>0.13</td>
<td>1.624</td>
<td>0.406</td>
<td>1.624</td>
</tr>
<tr>
<td>60</td>
<td>0.21</td>
<td>1.624</td>
<td>0.406</td>
<td>1.624</td>
</tr>
</tbody>
</table>

---

**Frequency Selectors**

**Available Output Power (dBm)**

**Transducer Power Gain (dB)**

---

**Input and Output Voltage Waveforms**

**Available Source Power (dBm)**

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Second Harmonic (dBc)</th>
<th>Third Harmonic (dBc)</th>
<th>Fourth Harmonic (dBc)</th>
<th>Fifth Harmonic (dBc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>-57.06</td>
<td>-63.36</td>
<td>-123.5</td>
<td>-183.3</td>
</tr>
<tr>
<td>30</td>
<td>-57.06</td>
<td>-63.36</td>
<td>-123.5</td>
<td>-183.3</td>
</tr>
<tr>
<td>40</td>
<td>-57.06</td>
<td>-63.36</td>
<td>-123.5</td>
<td>-183.3</td>
</tr>
<tr>
<td>50</td>
<td>-57.06</td>
<td>-63.36</td>
<td>-123.5</td>
<td>-183.3</td>
</tr>
<tr>
<td>60</td>
<td>-57.06</td>
<td>-63.36</td>
<td>-123.5</td>
<td>-183.3</td>
</tr>
</tbody>
</table>

---

**High Supply Current**

**Fundamental Output Power (dBm)**

---
Load-Pull Contours

At load that gives minimum bias current:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BiasCurrent (mA)</td>
<td>0.153</td>
</tr>
<tr>
<td>Zout @ MinCurrent</td>
<td>5.113</td>
</tr>
<tr>
<td></td>
<td>(109 57.37)</td>
</tr>
<tr>
<td></td>
<td>0.060/122.460</td>
</tr>
<tr>
<td>PAE @ MinCurrent</td>
<td>10.024</td>
</tr>
<tr>
<td>GainComp @ MinCurrent</td>
<td>1.0016</td>
</tr>
<tr>
<td>Zin @ MinCurrent</td>
<td>8.875</td>
</tr>
<tr>
<td></td>
<td>(2.604)</td>
</tr>
<tr>
<td></td>
<td>1.109</td>
</tr>
<tr>
<td>PAE @ MinCurrent</td>
<td>15.102</td>
</tr>
<tr>
<td>GainComp @ MinCurrent</td>
<td>0.0013</td>
</tr>
<tr>
<td></td>
<td>(15.131)</td>
</tr>
</tbody>
</table>

At load that gives maximum PAE:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BiasCurrent @ MaxPAE</td>
<td>0.156</td>
</tr>
<tr>
<td>GainComp @ MaxPAE</td>
<td>13.956</td>
</tr>
<tr>
<td></td>
<td>(26.320)</td>
</tr>
<tr>
<td></td>
<td>0.087/116.087</td>
</tr>
<tr>
<td>PAE @ MaxPAE</td>
<td>4.371</td>
</tr>
<tr>
<td>GainComp @ MaxPAE</td>
<td>1.480</td>
</tr>
<tr>
<td>Zin @ MaxPAE</td>
<td>8.296</td>
</tr>
<tr>
<td></td>
<td>(4.105)</td>
</tr>
<tr>
<td></td>
<td>0.789</td>
</tr>
<tr>
<td>PAE @ MaxPAE</td>
<td>15.032</td>
</tr>
<tr>
<td>GainComp @ MaxPAE</td>
<td>23.111</td>
</tr>
</tbody>
</table>

At load that gives minimum gain compression:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BiasCurrent @ MinGainComp</td>
<td>0.148</td>
</tr>
<tr>
<td>GainComp @ MinGainComp</td>
<td>7.213</td>
</tr>
<tr>
<td></td>
<td>(26.702)</td>
</tr>
<tr>
<td></td>
<td>0.75/125.233</td>
</tr>
<tr>
<td>PAE @ MinGainComp</td>
<td>3.002</td>
</tr>
<tr>
<td>GainComp @ MinGainComp</td>
<td>0.530</td>
</tr>
<tr>
<td>Zin @ MinGainComp</td>
<td>8.231</td>
</tr>
<tr>
<td></td>
<td>(4.862)</td>
</tr>
<tr>
<td></td>
<td>4.544</td>
</tr>
<tr>
<td>PAE @ MinGainComp</td>
<td>16.006</td>
</tr>
<tr>
<td>GainComp @ MinGainComp</td>
<td>25.051</td>
</tr>
<tr>
<td></td>
<td>(25.051)</td>
</tr>
</tbody>
</table>

At load that gives minimum 3rd-order IMD:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BiasCurrent @ MinIMD3</td>
<td>0.147</td>
</tr>
<tr>
<td>GainComp @ MinIMD3</td>
<td>0.085</td>
</tr>
<tr>
<td></td>
<td>(47.503)</td>
</tr>
<tr>
<td></td>
<td>0.723/44.69</td>
</tr>
<tr>
<td>PAE @ MinIMD3</td>
<td>3.456</td>
</tr>
<tr>
<td>GainComp @ MinIMD3</td>
<td>0.047</td>
</tr>
<tr>
<td>Zin @ MinIMD3</td>
<td>0.840</td>
</tr>
<tr>
<td></td>
<td>(1.277)</td>
</tr>
<tr>
<td></td>
<td>4.095</td>
</tr>
<tr>
<td>GainComp @ MinIMD3</td>
<td>15.054</td>
</tr>
<tr>
<td></td>
<td>(15.201)</td>
</tr>
<tr>
<td>PAE @ MinIMD3</td>
<td>0.147</td>
</tr>
<tr>
<td>GainComp @ MinIMD3</td>
<td>12.000</td>
</tr>
<tr>
<td></td>
<td>(20.000)</td>
</tr>
<tr>
<td></td>
<td>0.688/160.688</td>
</tr>
<tr>
<td>PAE @ MinIMD3</td>
<td>3.456</td>
</tr>
<tr>
<td>GainComp @ MinIMD3</td>
<td>4.731</td>
</tr>
<tr>
<td>Zin @ MinIMD3</td>
<td>0.840</td>
</tr>
<tr>
<td></td>
<td>(1.277)</td>
</tr>
<tr>
<td></td>
<td>4.095</td>
</tr>
<tr>
<td>GainComp @ MinIMD3</td>
<td>15.054</td>
</tr>
<tr>
<td></td>
<td>(15.201)</td>
</tr>
</tbody>
</table>

Output power spectrum, near fundamental frequencies, with load reflection coefficient chosen by marker m1.
Overlay Of Power Contours And PAE
PDK Toolbars are implemented for each individual process.
Example of Desktop DRC

Step 1 – Invoke the Desktop DRC Tool

Step 2 – Select Rule File

Step 3 – Click on “Run”
Desktop DRC Results Viewer

Design: adeno_DRC_tdr

Job name: adeno_DRC_tdr_drc

Error

- ABP to ABP < 4.00
  - Design: 829.500 -5.500
- MET1, NT1 coincident
  - Design: 594.995 9.991
  - Design: 594.995 -48.495
  - Design: 524.005 54.995
- MET2, ABP coincident
  - Design: 829.000 -5.000
- NT1 on CTG-labeled cap
  - Design: 829.000 -5.000
- NT1 to NT1 < 2.00
  - Design: 829.500 -5.500
- NT2 to NT2 < 2.00
- Unsupported Air Bridge
  - Design: 888.500 -342.000
- VIA to VIA < 100.0
  - Design: 119.132 -266.279

Number of errors: 13

Design rule: C:\0_Europe_Trip\Final_Revamped_Projects\masc_hdi_der

Check issues at edges of lines.
Error Summary

![Error Summary Image]

- Components not in schematic: 20
- Components not in layout: 32
- Nodal Mismatches: 36
- Parameter Mismatches

<table>
<thead>
<tr>
<th>Component (92)</th>
<th>Nodal (36)</th>
<th>Parameter (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC_Bus1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>GROUND</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>R</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>T1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>V_DC</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>t_canc_cap</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>t_canc_mkn</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>t_canc_mkn</td>
<td>30</td>
<td>48</td>
</tr>
<tr>
<td>t_canc_mkn</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>t_canc_mkn</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>t_canc_mkn</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>t_canc_mkn</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>t_canc_mkn</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>t_canc_mkn</td>
<td>6</td>
<td>12</td>
</tr>
</tbody>
</table>

Component Count: 104

Schematic Layout:

- DC_Bus1: 2
- GROUND: 18
- R: 4
- T1: 2
- V_DC: 5
- t_canc_cap: 0
- t_canc_mkn: 10
- t_canc_mkn: 30
- t_canc_mkn: 0
- t_canc_mkn: 3
- t_canc_mkn: 10
- t_canc_mkn: 3
- t_canc_mkn: 2
- t_canc_mkn: 6

Run
- Run hierarchically
- Find parameter mismatches

Save As
- Help
3D Rendering Of Design
Three Stage Amplifier
Final Assembly Ready For Test
Cascade Elite 300 Prober
In theory there is no difference between theory and practice. In practice there is.

-Yogi Berra
Momentum Simulation For First Stage, Start Of Investigating Differences
Schematic Vs. Schematic W/Momentum Results
The Additional Coupling Within The First Stage Shows A Frequency Shift To The Lower Frequency Range

First Stage performance with empirical models

First Stage performance with Momentum results
WPAN Wireless Library Product Features

HRP Source

• Preamble:
  • - Time domain
  • - Frequency domain

• Header
  – - PHY header
  – - MAC header
  – - CRC, Scrambling
  – - RS coding, Outer interleaver
  – - 1/3 Convolutional coding, bit interleaver, tone interleaver

• Data
  – - Sub-packet structure
  – - CRC, Scrambling
  – - RS coding, Outer interleaver
  – - Puncturing convolutional coding, bit interleaver, tone interleaver

• OFDM modulation

Measurement Test Benches:

• Spectrum
• CCDF
• Waveform
• EVM

HRP Receiver

• Frame and frequency synchronization
• De-framing
• Cyclic prefix removing
• Channel estimator
• Phase tracking
• Equalizer
• Demapper
• Decoder

Measurement Test Benches:

• RawBER and BER on AWGN
• RX Sensitivity
HRP Transmitter Test Benches
Initial WPAN Simulations
Thank You