Power Amplifier MMICs for mmWave 5G

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Presentation Outline

- Likely operating bands for mmWave 5G
- Solid-state process options
- SMT packaging options
- mmWave 5G PA design examples:
  - 28GHz PA in plastic overmoulded QFN package
  - 39GHz PA in air-cavity plastic
  - 26GHz PA in custom laminate dual-channel package
  - Dual-band PA (26GHz and 32GHz bands)
What Operating Bands will be used for mmWave 5G?

- 28GHz US band soon to be auctioned (FCC auction 101)
- The 24GHz band (24.25-24.45, 24.75-25.25 GHz) will follow (FCC auction 102)
- Additional European bands;
  - 31.8 to 33.4 GHz RSPG “Future 5G Band”
  - 40.5 to 43.5 GHz
Process Options for mmWave PAs

<table>
<thead>
<tr>
<th>Function</th>
<th>Single die saturated RF output power</th>
<th>Cost per unit area</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMOS</td>
<td>10 to 20mW</td>
<td>$</td>
</tr>
<tr>
<td>SiGe</td>
<td>50 to 100mW</td>
<td>$$</td>
</tr>
<tr>
<td>GaAs PHEMT</td>
<td>2 to 3W</td>
<td>$$$</td>
</tr>
<tr>
<td>GaN</td>
<td>10 to 15W</td>
<td>$$$$$</td>
</tr>
</tbody>
</table>

- Power levels are the approximate practical levels for a single commercial PA die, not the absolute maximum achievable power in the technology
- The cost column is comparative, it is not intended to indicate a multiplying factor
## Packaging Options and Trends
For mmWave blocks

The frequencies in the table below are guidelines rather than hard limits:

<table>
<thead>
<tr>
<th>Style</th>
<th>Typical Frequency</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over-moulded plastic</td>
<td>To ~ 30GHz</td>
<td>Normally uses custom leadframe</td>
</tr>
<tr>
<td>Air-cavity plastic</td>
<td>To ~ 42GHz</td>
<td>Normally uses custom leadframe</td>
</tr>
<tr>
<td>Laminate</td>
<td>To ~ 45GHz</td>
<td>Normally custom designed for higher frequency use</td>
</tr>
<tr>
<td>Wafer Level CSP</td>
<td>To ~ 80GHz</td>
<td>Die is flip-chipped</td>
</tr>
<tr>
<td>Multi-Chip Modules</td>
<td>To 100GHz</td>
<td>Bare die assembled into custom substrate</td>
</tr>
<tr>
<td>Integral Antennas</td>
<td>&gt; 100GHz</td>
<td>Multi-elements commonly used</td>
</tr>
</tbody>
</table>
28GHz PA - Overview

• Three stage 50Ω matched PA with on-chip RF transmit power detector
• Designed on the PE15 process of WIN Semiconductors
• Packaged in a 4mm x 4mm over-moulded plastic QFN
• Performance summary:
  – Frequency range: 26 to 30GHz
  – Gain ~ 20dB
  – P-1dB ~ 24.5dBm to 26dBm (280 to 400mW)
  – PAE at P-1dB ~ 25 to 30%
  – PAE at -35dBc IMD3 ~ 7 to 9%
• All measurements made with PA solder attached to representative PCB
28GHz PA Evaluation PCB

All measured data that follows is referenced to package pins using TRL calibration
28GHz PA - Measured to Simulated

- S11_meas
- S21_meas
- S11_mod
- S21_mod

Start: 20.0000 GHz
Stop: 36.0000 GHz
28GHz PA - Measured to Modelled S-parameters

Measured results for 3 samples

Measured to modelled
28GHz PA - Measured to Simulated
Measured Output IP3

Input tone powers of -14dBm to -4dBm per tone, 100MHz tone spacing
Comparison of Measured to Modelled PAE vs Pout at 29.2GHz
Measured RF Power Detector

Two samples, 3 frequencies versus RF output power
39GHz PA Overview

- Process: 0.15µm PHEMT
- Package: Air cavity QFN
- Covers 39GHz 5G band (good performance 37 – 42GHz)
- Measurement conditions:
  - Packaged part assembled onto laminate evaluation PCB
  - Measurements referenced to package
  - Ambient = 25°C
  - Vdd = 6V
  - Idq = 1260mA (131mA/mm)
  - Micro-strip style PCB
  - All measurement results are CW
39GHz PA in 5mm x 5mm Air-Cavity Plastic
39GHz PA in 5mm x 5mm Air-Cavity QFN
Measurements on eval PCB referenced to package ports
39GHz PA – Pout, Gain and Id vs. Pin at 39GHz
39GHz PA in 5mm x 5mm Air-Cavity QFN

Measurements on eval PCB referenced to package ports
PA for 26GHz 5G Pioneer Band - Overview

- Covers 24 – 28GHz (pioneer band is 24.25 – 27.5GHz)
- Includes on-chip temperature compensated power detector
- Die size: 3.5mm x 1.2mm (x-dimension can be reduced to 3mm)
- Fabricated on a 0.15µm PHEMT process from WIN
- Gain ~ 22dB; P-1dB ~ 26dBm; PAE ~ 30%
Temperature-Compensated Power Detector
RFOW Measured Performance

S-parameters

- Biased at 6V Vds and 210mA Ids
RFOW Measured Performance

S-parameters

- Biased at 6V Vds and 210mA Ids
- Covers 24 – 28GHz with:
  - Gain > 21dB
  - S11 < -13dB
  - S22 < -10dB
- Dashed trace is simulated
RFOW Measured Performance Compared to Simulated

- 5 RFOW measured parts compared to simulated
RFOW Measured Performance

Power Compression

- P-1dB ~ 26dBm
- PAE @ P-1dB ~ 30%
- PAE @ 6dB BO ~ 9%
Packaging of Dual Channel Component

Overview

- Laminate substrate for base and lid
- QFN package with solid Cu base
- Custom design for optimum RF performance
- Two die co-packaged to yield dual-channel part
- Package manufacture and assembly by Filtronic
Packaging of Dual Channel Component

Assembly Detail
Evaluation Board for Dual Channel Component
Calibration of Measured Data
TRL Calibration Tile Used to Reference Data to Package Pads
Evaluation Board for Dual Channel Component
Connection of DC Bias Cables
Measured Performance of Packaged Components
S-parameters Referenced to Package Pads

- Both channels (A and B) plotted on the same graph
Measured Performance of Packaged Components
Packaged Performance Compares to RFOE

- Dashed traces are RFOE measured performance
- Both channels (A and B) of the packaged part also shown
Measured Performance of Packaged Components

S-parameters of One PA Over Temperature
Measured Performance of Packaged Components

Power Compression of Typical PA Over Temperature

25°C

-40°C

85°C

<table>
<thead>
<tr>
<th>Freq</th>
<th>24.25GHz</th>
<th>26GHz</th>
<th>27.5GHz</th>
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<tbody>
<tr>
<td>P-1dB</td>
<td>26.6dBm</td>
<td>25.4dBm</td>
<td>26.2dBm</td>
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<td>26.2dBm</td>
<td>25.9dBm</td>
<td>26.3dBm</td>
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<tbody>
<tr>
<td>P-1dB</td>
<td>25.8dBm</td>
<td>24.9dBm</td>
<td>25.7dBm</td>
</tr>
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</table>
Measured Performance of Packaged Components

PAE of Typical PA Over Temperature

- **25°C**
  - PAE at P-1dB ~ 25%

- **-40°C**
  - PAE at P-1dB ~ 27%

- **85°C**
  - PAE at P-1dB ~ 23%
Measured Performance of Packaged Components
Detected RF Power of Typical PA Over Temperature

- Temperature compensated RF power detector included on-chip
- Plotted performance is at 26GHz:
Measured Performance of Packaged Components

IP3 of Typical PA Over Temperature

![Graph showing IP3 of Typical PA Over Temperature](image-url)
Dual Band PA - Background

- Considerable time and money is currently being invested in developing mmWwave technology for 5G
- Much debate about suitable frequency bands
- In Europe, RSPG recommended bands are:
  - 26GHz Band (24.25 to 27.5GHz) – “Pioneer” 5G Band
  - 32GHz Band (31.8 to 33.4GHz) – Future 5G Band
- In the US FCC licensed bands:
  - 28GHz Band (27.5 to 28.35GHz)
  - 37 & 39GHz Band (37 to 38.6GHz and 38.6 to 40GHz)
- Single worldwide 5G band unlikely
- Dual-band / Multi-band, mmWave components attractive for high volume applications
Dual Band PA – Design Strategy

• 1st Design 2 single band PAs, one for each band
  – Use multiple power combined transistors to achieve gain and power at mm-wave frequencies
  – Use common topology, transistor sizes and bias point

• Convert the two individual PAs into a single switched design
  – Key RF elements switched in and out of circuit:
    o Lengths of transmission line
    o Capacitors

• Switches realized by PHEMT transistors
  – OFF capacitance problematic at mm-wave!
Dual Band PA – Layout

RFIn

Vg1
Vg23
Vgg
Vctrl2

Vctrl1
Vd12
Vd3

RFOut
Dual Band PA – Simulated Small Signal

[Graphs showing simulated small signal behavior for dual band PA]
Dual Band PA – Simulated Large Signal

More details: [https://www.plextekrfi.com/mm-wave/mm-wave-5g/](https://www.plextekrfi.com/mm-wave/mm-wave-5g/)
Conclusions

• Much work is currently underway in the development of mm-wave components targeting the expected 5G mm-wave bands

• Operating bands still to be confirmed, Ka-band looking likely but a single allocation worldwide is not realistic.

• Four mmWave 5G PA design examples presented:
  1. 28GHz PA in plastic overmoulded QFN package
  2. 39GHz PA in air-cavity plastic
  3. 26GHz PA in custom laminate dual-channel package
  4. Dual-band PA (26GHz and 32GHz bands)

• For more details, see: www.PlextekRFI.com