Highly Efficient High Power PA Design for Resonant WPT
March 2018
Outline

• Brief company overview
• WPT applications
• MHz vs kHz
• Tx topologies for WPT
• High power PA design for WPT with Gan Systems devices
  – 300W Class EF2 PA with GS66508B
  – 100W Class FE2 PA with GS61008P
• GaN Systems offering for WPT application
Market leader for gallium nitride (GaN) power transistors
• GaN-on-Silicon power transistors for the power conversion market
• Industry’s most extensive & highest-performance product line
  • Enhancement mode devices
  • 100V & 650V devices; industry-best performance

Global company with decades of experience in GaN
• HQ and R&D in Ottawa, Canada
• Sales & App. Eng. in Germany, Japan, China, Taiwan, Korea, USA
• World-class fabless manufacturing and advanced packaging
• Parts shipping overnight from Mouser since 2014
A complete GaN product portfolio

Product characteristics
- Low resistance
- Very high current
- 100V and 650V product families

GaN Systems device on a traditional T0-247 package
Wireless Power Transfer

Everything.
Applications for Cutting the Cord

• Laptops
• Phones
• Power Tools
• Home appliances
• eBikes
• Drones
• Robots
• ....
WPT Trends and Technology Drivers

**Trends**
- Fast charge, variable Tx/Rx spacing, increasing power levels

**Technology Drivers**
- High switching frequency, high current, high voltage

30W → 65W → 180W → 1000 to 2500W → 6000 to 22000W
### Power Transfer Standards

<table>
<thead>
<tr>
<th>Standard organization</th>
<th>Wireless Power Consortium (Qi)</th>
<th>AirFuel Alliance (Rezence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>Inductive</td>
<td>Resonant</td>
</tr>
<tr>
<td>Frequency range</td>
<td>80 to 300 kHz</td>
<td>6.78 MHz</td>
</tr>
<tr>
<td>Max. Xfr range</td>
<td>5 mm</td>
<td>50 mm</td>
</tr>
<tr>
<td>No. charging devices</td>
<td>One</td>
<td>Multiple ok.</td>
</tr>
<tr>
<td>Communications system</td>
<td>Load modulation</td>
<td>Bluetooth</td>
</tr>
</tbody>
</table>

- **WPC**
  - Formerly Qi
  - Primarily inductive
- **AirFuel**
  - Formerly PMA, AW4P, Rezence
  - Primarily resonant

**GaN compatible with all standards**
**MHz vs kHz frequencies – Inverter**

**kHz WPT systems**
- Good efficiency **only** for very low distances, a few millimeters, and **only** when the coils are precisely aligned.
- Efficiency drops rapidly as the coils move apart and the induced voltage at the receiver becomes very low and therefore is inefficient to rectify.
- Uses a lot of ferrite to guide the magnetic flux, this limits the position of the receiver to a fixed position.

**MHz WPT systems**
- High power transfer efficiency across a much greater distance.
- Allows for better tolerances to coil misalignment.
- The inverter ‘sees’ more of the receiver, i.e. the reflected resistance \( R_{\text{ref}} \) of the load increases.
- Therefore power can be transferred at lower coil currents.
- Lower coil currents mean less conduction losses in the inverter, resulting in higher inverter efficiency and higher system efficiency.

**Equation**
\[
R_{\text{ref}} = \frac{\omega^2 M^2}{R_{\text{Load}}}
\]
Wireless Power System

Source - Transmitter (Tx)
1) Amplifier
2) Impedance Matching Network
3) Tx Coil

Device - Receiver (Rx)
1) Rx Coil
2) Impedance Matching Network
3) Rectifier
4) Load

GaN FETs are used in the Transmitter Amplifier
Switch mode PA typologies analysis

Class D/E/EF2 topologies

**Class D with ZVS**

\[
P = \frac{8}{\pi^2} \frac{V_R^2}{R_L} = \frac{8}{\pi^2} \frac{R_L}{(R_L + r_{sat})^2} V_{cc}^2.
\]

\[
\eta = \frac{P}{P_0} = \frac{8}{\pi^2} \approx 81\%.
\]

**Class E with shunt C**

\[
R = \frac{8}{\pi^2 + 4} \frac{V_{cc}^2}{P_{out}} = 0.5768 \frac{V_{cc}^2}{P_{out}}.
\]

\[
\eta = \frac{P_{out}}{P_0} = \frac{P_0 - P_{sat}}{P_0} = 1 - \frac{P_{sat}}{P_0}.
\]

**Class EF2**

\[
P_o = 0.6105 \frac{V_{IN}^2}{R_L}.
\]

\[
\eta = \frac{1}{1 + P_{L_1} + P_{DS} + P_{C_1} + P_{L_2}C_2 + P_{L_3}C_3 + P_f}.
\]

Circuit diagram of the Class EF or Class E/F inverter.
Efficiency comparison typologies Class D/E/EF2

- Simulations of MOSFET at 6.78MHz, 25V DC
  - Class D: Max efficiency 82.4%
  - Class E: Max efficiency 93.9%
  - Class EF2: Max efficiency 93.4%
Impedance window comparison typologies Class D/E/EF2

- Single ended configuration at 6.78MHz, 25V DC, red = power, blue = efficiency
  - Class D: low impedance point is point of maximum power and efficiency, power is limited by dissipation power, so PA cannot operate at maximum power and efficiency
  - Class E: low impedance point is the maximum power point, not near its optimum power and efficiency point
  - Class EF2: both efficiency and power are maximized

Class D with ZVS  
Class E with Cshunt  
Class EF2
GaN Systems WPT Class EF2 turn key PA solution

- Device 650V, GS66508B, Push Pull
- Thermal solution: copper coins solder down
- Design built in EMI filter
- Unique output filter network design naturally provide constant current

Designed to simultaneously achieve power, efficiency, EMI and constant current behavior.
150W PA Efficiency

- 50ohm load
- 156W output
- 93% efficiency
- T rise 2 degree at device

- 50ohm load
- 150W output
- 87% efficiency
- T rise 2 degrees at device
At 150W output power, 3\textsuperscript{rd} harmonic rejection is -42dBc with EMI filter, more than -60dBc rejection on high order harmonics.
At 150W output power without EMI filter, hottest point is located at RF choke inductor 61 degree C.

Hottest point is located at 2\textsuperscript{nd} harmonic shunt inductor, 86 degree C, temperature at device is in control, less than 31 degrees C.
**150W PA System Test**

- **End to end efficiency = 86%**

**Power Ratings**
- Input Voltage = 43 V (DC)
- Input Current = 1.61 A (DC)
- Output Voltage = 74.8 V (rms)
- Output Current = 0.8 A (rms)
Turn key solution of Class EF2 70W/100W PA for WPT

GaN Systems WPT Class EF2 turn key PA solution

- Device 100V, GS61008P, Push Pull
- Thermal solution: copper coins solder down
- Design built in EMI filter
- Unique output filter network design naturally provide constant current

Designed to simultaneously achieve power, efficiency, EMI and constant current behavior.
70W PA Efficiency and Thermals

- 50ohm load
- 27V, 78W output
- 90% efficiency
- T rise is 2 degrees at the device

- 77W output power
- Warmest point is at RF choke, 48 deg. C
- Transistor temp is less than 31 deg. C

Thermal image with EMI filter at 27V
70W PA Class EF2 voltage waveforms

70W PA Class EF2 without EMI filter

- Low stress voltage wave at both devices at 27V
- $V_{\text{max}}/V_{\text{cc}} = 2.3$ at 50ohm
- Output current is not a perfect sine wave due to harmonics

70W PA Class EF2 with EMI filter

- Low stress voltage wave at both devices at 27V
- $V_{\text{max}}/V_{\text{cc}} = 2.6$ at 50ohm
- Output current is almost a perfect sine wave
High Power GaN devices for Resonant WPT

<table>
<thead>
<tr>
<th>GS61004B</th>
<th>GS61008B</th>
<th>GS66508B</th>
<th>DS66516B</th>
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<tbody>
<tr>
<td>• 300W CW at 50V</td>
<td>• 600W CW at 50V</td>
<td>• 600W CW at 100V</td>
<td>• 1000W CW at 100V</td>
</tr>
<tr>
<td>• 1 kHz – 150 MHz</td>
<td>• 1 kHz – 120 MHz</td>
<td>• 1 kHz – 80 MHz</td>
<td>• 1KHz – 80 MHz</td>
</tr>
<tr>
<td>• 40 dB gain at 10 MHz</td>
<td>• 40 dB gain at 10 MHz</td>
<td>• 37 dB gain at 10 MHz</td>
<td>• 37 dB gain at 10 MHz</td>
</tr>
<tr>
<td>• 91% efficiency at 10 MHz</td>
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GaN Systems enables compact, low cost, high power wireless charging
Conclusions

• **WPT is growing in many markets and applications**
  - Need high power, spatial freedom and high efficiency

• **MHz systems are better than kHz**
  - Wireless power is about mobility, you want to be able to charge and power devices without being limited to a fixed position. MHz provides this capability.

• **GaN Systems provides high performance solutions**
  - 100W and 300W PA kits demonstrate high efficiency at high power output
  - The Tx architecture design offers exceptional EMI performance
  - Enable end-to-end efficiency approaching 90%