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Comparison of 6.78 MHz Amplifier Topologies for 33W, Highly Resonant Wireless Power Transfer
Efficient Power Conversion Corporation
Agenda

• Wireless power trends
• AirFuel™ Class 4
• High power capable amplifiers
• Experimental results
• Summary

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Wireless Power Trends

Higher power

– More devices needing wireless power
  • Smartphones (~6 W)
  • Tablets (~13 W)
  • Small laptops (~25 W)

– Fast charging

– Move toward wireless power, not just charging
AirFuel Class 4 Operation

- $1.375 \text{ A}_{\text{RMS}}$ into the coil or de-rated at 33 W
- 6.78 MHz

AirFuel™ Alliance

- Devices
  - 1x Category 5 (20 W)
  - up to
  - 3x Category 3 (6.5 W)
• Differential mode ZVS class D
  – Robust to load variations
  – Requires level shifting gate driver

• Differential mode class E
  – Simple and low cost
  – Susceptible to load variations
ZVS Class D Design

• Analytical design: -50j Ω through +50j Ω & 1 Ω through 52 Ω

• Optimal $L_{ZVS}$ and dead-time:
  – EPC2007C (30 mΩ) = 390 nH, 8ns
  – EPC8010 (160 mΩ) = 500 nH, 3.5 ns

• Requires synchronous bootstrap
Class E Design

• Optimal load point analysis by simulation

• Realizable design FET selection:
  - EPC2012C (100 mΩ), $C_{sh} = 68$ pF
  - EPC2019 (50 mΩ), $C_{sh} = 0$ pF

• $L_e = 600$ nH, $L_{RFck} = 39$ μH

Ideal Waveforms

$V_{DS} \propto 3.56 \times V_{DD}$

50%
Class E Optimization

- LTSpice simulation: Total FET power loss
- Optimal load resistance – lowest cumulative FET loss over entire Load resistance range
Experimental Units

ZVS class D

- EPC2007C
- EPC8010

Class E

- EPC2012C
- EPC2019
Class D – EPC2007C

- Thermally limited at extreme load impedances
- 60Ω range class 4 capable
Class D – EPC8010

- Thermally limited at extreme load impedances
- 70\(j\,\Omega\) range class 4 capable
Class E – EPC2012C

- Thermally and voltage limited
- **25\text{j} \Omega** range class 4 capable
Class E – EPC2019

- Thermally and voltage limited
- **40j Ω** range class 4 capable
Efficiency ranges – all designs

Class D - wide variation due to wider impedance range
• Class E performance nearly identical when compared over same impedance range
• Class D yields greater improvement from lower $R_{DSon}$

<table>
<thead>
<tr>
<th>Topology</th>
<th>eGaN FET ($R_{DSon}$)</th>
<th>Efficiency Range at max. Power</th>
<th>Reactance Range</th>
<th>Relative Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZVS class-D</td>
<td>EPC8010</td>
<td>80.2% to 90.6%</td>
<td>-35j to +35j Ω</td>
<td>70j Ω</td>
</tr>
<tr>
<td></td>
<td>EPC2007C</td>
<td>87.5% to 92.8%</td>
<td>-15j to +45j Ω</td>
<td>60j Ω</td>
</tr>
<tr>
<td>Class-E</td>
<td>EPC2012C</td>
<td>85.1% to 90.4%</td>
<td>-20j to +5j Ω</td>
<td>25j Ω</td>
</tr>
<tr>
<td></td>
<td>EPC2019</td>
<td>82.8% to 88.6%</td>
<td>-20j to +20j Ω</td>
<td>40j Ω</td>
</tr>
</tbody>
</table>
Class E – Limitations

- 160 V limit – 80% of rated
- 100°C

Device Temperature [°C] vs. Reflected Resistance [Ω]

Voltage limited

Drain Voltage

Coil Current

- EPC2019
- EPC2012C
Summary

• 33 W wireless power amplifiers compared
  • Wider impedance range leads to lower cost systems
  • ZVS Class D: 75% wider impedance range than class E
  • Class E: Easier to drive and more popular
• eGaN FETs yield high efficiency at full power
  • Lower $R_{DSon}$ improves performance
  \[ \text{but higher } C_{OSS} \text{ leads to} \]
  • Higher soft-switching energy for class D
  • Design with negative $C_{sh}$ for Class E
The end of the road for silicon…

but a clear road ahead for GaN FETs and ICs!