**eGaN® ICs for Low Cost Resonant Wireless Power**

Yuanzhe Zhang, Ph.D., Director of Applications Engineering, Michael de Rooij, Ph.D., Vice President of Applications Engineering

Resonant wireless power systems use loosely-coupled, highly-resonant coils that are tuned to high frequencies (6.78 MHz or 13.56 MHz). The AirFuel™ Alliance has developed the standard for resonant wireless power applications. They address convenience-of-use issues such as source to device distance, device orientation on the source, multiple devices on a single source, higher power capability, simplicity of use, and imperfect placement. eGaN® FETs from EPC offer significantly lower capacitance and inductance with zero reverse recovery charge \(Q_{\text{DR}}\) in a smaller footprint for a given on-resistance \(R_{\text{DS(on)}}\) than comparable MOSFETs. This enables a number of applications that require higher switching frequency such as 6.78 MHz highly resonant wireless power transfer. eGaN ICs pair a FET with integrated gate driver that is optimally designed for the FET ensuring maximum possible system performance while simplifying design and lowering cost.

In this application note, we introduce two class-E amplifiers designed, built and tested using EPC’s new gate driver integrated FETs the EPC2112 and EPC2115 for operation as an AirFuel™ Alliance compatible wireless power amplifier.

Highly resonant wireless power systems operate at 6.78 MHz and eGaN® FETs have proven to yield higher efficiency and power density designs over MOSFET versions [1], [2]. The ability to integrate multiple devices, performing additional functions such as synchronous bootstrapping, on a single monolithic substrate [3], [4] has further enhanced the performance of wireless power amplifiers [5], [6], [7]. Operating at high frequencies requires high performance gate drivers and commercial gate drivers, such as the LM5113 [8], have traditionally been used to drive the eGaN FETs. The same concept of high performance applies to integrated gate drivers, but at reduced cost and complexity.

**Introducing the EPC2112 and EPC2115 eGaN ICs**

The lateral structure of eGaN FETs allows for monolithic integration of a gate driver and a power FET with the goal being to enhance performance, reduce cost and simplify design. The single FET EPC2112 [9] and Dual FET EPC2115 [10] eGaN ICs were designed with that in mind. Figure 1 shows the bump side of the EPC2115 and EPC2112 respectively. These ICs have a low bump count and only need an input signal and supply voltage to operate. The bump assignment is layout friendly, making designs easier to complete thereby ensuring high performance.

Monolithic integration of the gate driver to the FET offers the lowest possible common source inductance (CSI) as it is moved to within the IC structure. Furthermore the gate driver has been optimized to the FET being driven to offer maximum performance under any operating condition. These benefits are on top of the well-established low capacitance and inductance, and zero reverse recovery charge \(Q_{\text{RR}}\) that enable efficient operation at high switching frequencies such as 6.78 MHz in highly resonant wireless power transfer. The key characteristics of the EPC2112 and EPC2115 are given in table 1.

**Overview of the differential class-E amplifier for wireless power**

The operation of class-E amplifier has been explained in detail in the wireless power handbook [2]. The schematic of a single-ended class-E amplifier is shown in figure 2 and consists of a ground-referenced transistor (\(S_1\)), an RF choke \(L_{\text{RFck}}\), an extra inductor \(L_e\) and a shunt capacitor \(C_{\text{sh}}\). The load of the amplifier \(Z_{\text{Load}}\) represents the power transmitting coil and is assumed to be inductive that includes loss and transmitted power resistance. A capacitor \(C_\text{C}\) is connected in series for coil tuning. The resistance of the tuned coil is \(R_{\text{Load}}\)

<table>
<thead>
<tr>
<th>Part Number</th>
<th>(V_{\text{DS}})</th>
<th>(R_{\text{DS(on)}})</th>
<th>(Q_{\text{DS}})</th>
<th>(I_D)</th>
<th>Continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPC2112</td>
<td>200 V</td>
<td>40 mΩ</td>
<td>24 nC</td>
<td>10 A</td>
<td>25°C</td>
</tr>
<tr>
<td>EPC2115</td>
<td>150 V</td>
<td>88 mΩ</td>
<td>6.7 nC</td>
<td>5 A</td>
<td>23°C</td>
</tr>
</tbody>
</table>

Table 1. EPC2112 and EPC2115 key characteristics.
The amplifier operates at a fixed frequency with a fixed duty cycle of 50%. The transistor voltage and current waveforms under ideal operation is sketched in figure 3. Because of zero-voltage switching (ZVS) and zero-current switching (ZCS) at the optimum operating point, the class E amplifier has high efficiency (usually well above 90%).

Under ideal operating conditions the voltage stress on the transistor is higher than the supply voltage—approximately 3.56 times supply voltage, as shown in figure 3. However in a wireless power application it can be as high as 7 times when load impedance drops. This is important to note when selecting a suitable FET for a wireless power application where the device load can lead to large reflected resistance variations.

The design equations for differential class-E amplifier are given as follows:

\[
\begin{align*}
\omega \cdot C_{sh} \cdot R_{Load} &= 0.3672 \\
P_{Load} \cdot R_{Load} / V_{DD} &= 2.3072 \\
\omega \cdot L_e / R_{Load} &= 0.5762 \\
\omega \cdot L_{RFck} / R_{Load} &> 11
\end{align*}
\]

Where:
- \(\omega\) = Radian frequency of operation [rad/s],
- \(R_{Load}\) = Optimum load resistance [Ω],
- \(P_{Load}\) = Load power [W],
- \(C_{sh}\) = Shunt Capacitance [F],
- \(V_{DD}\) = Amplifier main supply voltage [V],
- \(L_e\) = Extra inductor for the class-E amplifier [H],
- \(L_{RFck}\) = RF choke of the class-E amplifier [H]

The value for the actual shunt capacitors \((C_{sh1} \text{ and } C_{sh2})\) is calculated by removing the device output capacitance portion as follows:

\[
C_{sh1} = C_{sh2} = C_{sh} - C_{OSSQ}
\]

And \(C_{OSSQ}\) is the charge equivalent output capacitance at the drain voltage of the device and can be approximated as follows:

\[
C_{OSSQ} = \frac{1}{V_{DS, EQ}} \int_0^{V_{DS, EQ}} C_{OSS} (V_{DS}) dV_{DS}
\]

\[
V_{DS, EQ} \approx 3.56 V_{DD} / \sqrt{2} = 2.5 V_{DD}
\]

**Design examples**

These eGaN ICs will be evaluated in two design examples: an AirFuel class 3 [11] amplifier using EPC2115 and a class 4 [12] amplifier using EPC2112. The schematic of the differential class E amplifier is shown in figure 4. Using a similar analysis presented in [13], the optimum \(R_{Load}\) for the class 3 design is 40 Ω; and 42 Ω for class 4 design. The specifications and design parameters are then calculated using the equations and the results are shown in table 2.

| #1 Class 3 | EPC2115 | 16 | 0.8 | 22 | 540 | 68 |
| #2 Class 4 | EPC2112 | 33 | 1.375 | 22 | 680 | 0 |

**Table 2. Design parameters.**
**Amplifier evaluation**

Two differential class-E amplifiers were designed and built as the EPC9088 and EPC9089 development boards for class 3 and class 4 respectively. Photos of each configured amplifier are shown in figure 5. The $L_e$ for EPC9088 is a 540 nH custom made ferrite core using carbonyl SF iron powder core 0.37 inch diameter with 13 turns of 20 AWG wire; while for EPC9089 a standard 680 nH low-profile ferrite inductor (Vishay part number IHLP2020BZER6R8M01) was used.

A load-pull test method was used to evaluate the amplifiers. The test stops when either the device temperature reaches or exceeds 100°C or the drain voltage reaches or exceeds 80% of rated value. No heat sink was mounted and no forced air cooling was used. The measured total amplifier efficiency (including logic and gate driver power consumption) over a reflected load impedance range is shown in figure 6 and figure 7 for the EPC9088 and EPC9089 amplifiers respectively. Example waveforms of output current and FET drain voltage are shown in figure 8.

**Summary**

In this application note, two eGaN ICs, the EPC2112 and EPC2115, were introduced and evaluated in differential class-E amplifiers suitable for a wireless power system operating to the AirFuel standard. The built-in gate drivers in the ICs simplify the design and board layout that contributes to cost reduction for the amplifier.
References:


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