# eGaN® FETs for Low Cost Resonant Wireless Power Applications

*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 ($Q_{RR}$) in a smaller footprint for a given $R_{DS(on)}$ than comparable MOSFETs. This enables a number of applications that require higher switching frequency such as 6.78 MHz highly resonant wireless power transfer.***

In this application note, we will present a differential class E amplifier using EPC2037 for 6.78 MHz loosely coupled highly resonant wireless power applications. A photo of the EPC2037 die is shown in figure 1, with its specifications given in table 1. It has very low gate charge and parasitics. As a result, no dedicated gate driver chips are required and it can be driven directly from logic.

**Class E amplifier design basics**

The schematic of a single-ended class E amplifier is shown in figure 2. It consists of a ground-referenced transistor ($Q_1$), an RF choke ($L_{RFck}$), an extra inductor ($L_e$) and a shunt capacitor ($C_{sh}$). The load of the amplifier ($Z_{Load}$) represents the power transmitting coil and is assumed to be inductive. A capacitor ($C_s$) is connected in series for coil tuning. The resistance of the tuned coil is $R_{Load}$. 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%).

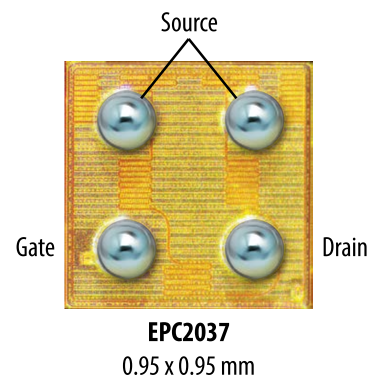


*Figure 1: Mounting side of EPC2037 eGaN FET Dimension: 0.9 x 0.9 mm*

| EPC Part Number | $V_{DS}$ (V) | $R_{DS(on)}$ @5 V (mΩ) | $Q_G$ @5 V Typ (pC) | $Q_{GS}$ Typ (pC) | $Q_{GD}$ Typ (pC) | $Q_{OSS}$ (pC) | $I_D$ (A) | Package (mm) |
|---|---|---|---|---|---|---|---|---|
| EPC2037 | 100 | 550 | 115 | 32 | 25 | 600 | 1.7 | BGA 0.9 x 0.9 |

*Table 1. EPC2037 specifications*

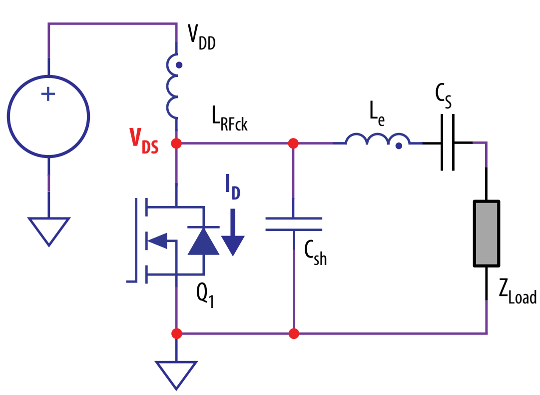


*Figure 2. Schematic of a single-ended class E amplifier*

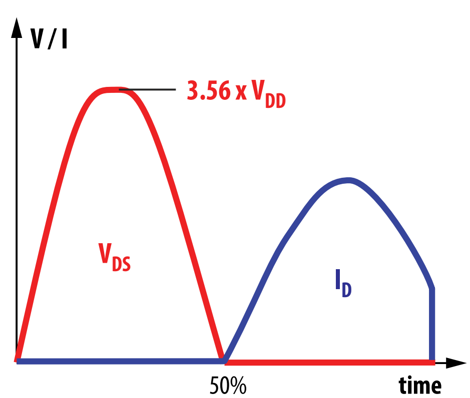


*Figure 3. Ideal FET voltage and current waveforms for the class E amplifier*

However, the voltage stress on the transistor is higher than the supply voltage. While 3.56 times supply voltage is shown in figure 3 for ideal operation, it can be as high as 7 times when load impedance changes. Therefore, despite the high efficiency, it is challenging to design a class E amplifier that works for a wide load impedance range, which is generally required in wireless power systems.

The design equations for a class E amplifier with an RF choke are well-known [1], summarized as follows:

$$\omega \bullet L_{RFck}/R_{Load} \rightarrow \infty$$
$$\omega \bullet C_{sh} \bullet R_{Load} = 0.1836$$
$$P_{Load} \bullet R_{Load}/V_{DD}^2 = 0.5768$$
$$\omega \bullet L_e/R_{Load} = 1.152$$

Given $R_{Load}$, $P_{Load}$ and operating frequency, the values of the supply voltage ($V_{DD}$), the extra inductor ($L_e$) and the shunt capacitor ($C_{sh}$) can be calculated.

The RF choke only needs to be large enough such that the deviation of the amplifier parameters can be neglected. According to the analysis in [2], it can be written as:

$$\omega \bullet L_{RFck}/R_{Load} > 22$$

The third equation reveals that, when the load resistor is fixed, the output power is limited by the supply voltage.

**Differential class E amplifier**

In order to get higher output power without increasing the voltage stress on the transistor, we need to consider the differential class E topology, as shown in figure 4. Note that the ideal switch ($Q_1$ in figure 3) is replaced by the actual eGaN FET. As a result, the equivalent shunt capacitance is the sum of the output capacitance of the FET ($C_{OSSQ}$) and the shunt capacitor ($C_{sh}$). $Q_1$ and $Q_2$ are driven by complementary signals. For design purposes, the circuit can be simplified according to half-circuit analysis. First, the load (and series tuning capacitor $C_s$) can be divided into two parts, resulting in a symmetrical circuit shown in figure 5. Then, taking half of the circuit results in figure 6. Therefore, in the design of a differential class E amplifier, the external components ($L_e$, $C_{sh}$) are the same as designed for $Z_{Load}/2$, or equivalently $R_{Load}/2$ and for $P_{Load}/2$ in the single-ended configuration.

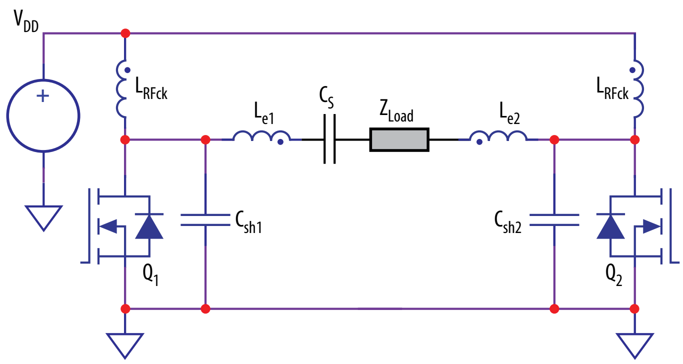


*Figure 4. Schematic of a differential class E amplifier*

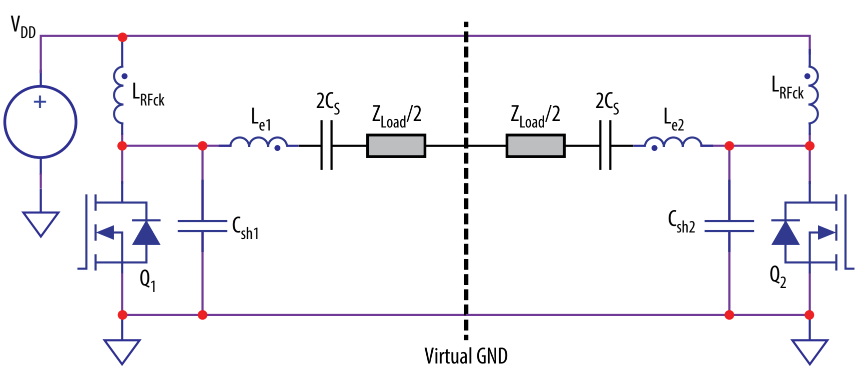


*Figure 5. Half-circuit analysis of a differential class E amplifier*

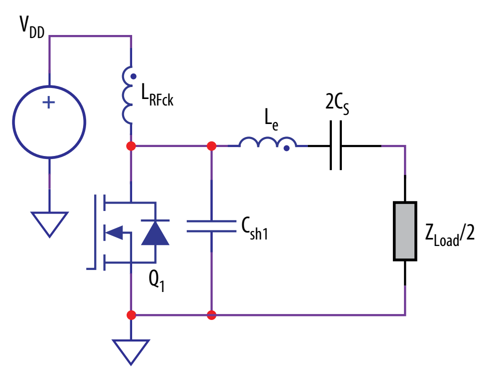


*Figure 6. Equivalent circuit for designing a differential class E amplifier*

The modified design equations for differential class E amplifier are listed below.

$$\omega \cdot C_{sh} \cdot R_{Load} = 0.3672$$
$$P_{Load} \cdot R_{Load} / V_{DD}^2 = 2.3072$$
$$\omega \cdot L_e / R_{Load} = 0.5762$$
$$\omega \cdot L_{RFck} / R_{Load} > 11$$

Similar to the case of the single-ended class E amplifier, given $R_{Load}$, $P_{Load}$ and operating frequency, the values of the supply voltage ($V_{DD}$), the extra inductor ($L_e$) and the shunt capacitor ($C_{sh}$) can be calculated. Note that $C_{sh}$ in the equation is the sum of the actual shunt capacitor ($C_{sh1}$, or $C_{sh2}$) and the output capacitance of the FET ($C_{OSSQ}$).

$$C_{OSSQ} = \frac{1}{V_{DD}} \int_0^{V_{DD}} C_{OSS}(v_{DS}) dv_{DS}$$

The value for those actual shunt capacitors ($C_{sh1}$ and $C_{sh2}$) is therefore:

$$C_{sh1} = C_{sh2} = C_{sh} - C_{OSSQ}$$

| $R_{Load,N}$ [Ω] | $L_{e1}$, $L_{e2}$ [nH] | $C_{sh1}$, $C_{sh2}$ [pF] |
|---|---|---|
| 20 | 270 | 417 |
| 30 | 406 | 272 |
| 40 | 541 | 201 |
| 50 | 677 | 159 |

*Table 2. The values of $L_e$ and $C_{sh}$ for different $R_{Load,N}$*

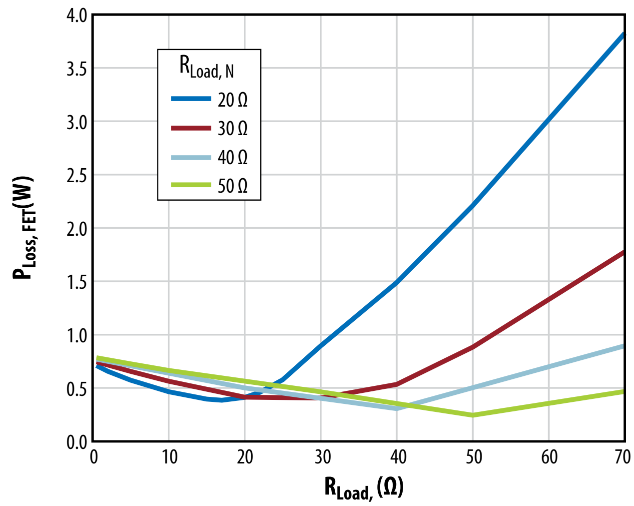


*Figure 7. Simulated FET losses for a range of $R_{Load}$ in the differential class E amplifier with different nominal $R_{Load,N}$*

**Nominal load and ideal operation**

As mentioned above, the design equations require a specified nominal load resistor, denoted as $R_{Load,N}$ in the following discussions. The actual value of $R_{Load}$ seen by the amplifier, however, may be different from $R_{Load,N}$. Therefore, the amplifier needs to handle a certain range of $R_{Load}$. For instance, for one of the AirFuel Class 2 [3] standard coils, the required load range $R_{Load}$ is from 6.5 Ω to 70 Ω.

When $R_{Load} \neq R_{Load,N}$, the amplifier efficiency drops due to either reverse conduction losses or switching ($C_{OSS}$) losses [4]. The goal is therefore to select the optimum nominal $R_{Load,N}$ so that the losses over the entire $R_{Load}$ range is minimum. For each specified $R_{Load,N}$, the values of $L_e$ and $C_{sh}$ are calculated according to the design equations and listed in table 2.

LTSpice simulation with EPC2037 device model is used to help determine the optimum $R_{Load,N}$. The differential class E amplifier in figure 4 is simulated for the desired $R_{Load}$ range and the losses of the FETs are recorded. Shown in figure 7 as an example, 20 Ω $R_{Load,N}$ is a bad choice as the FET losses increase rapidly at high $R_{Load}$ values. The optimum $R_{Load,N}$ is between 40 Ω to 50 Ω, resulting in lowest FET losses over the wide range. Further simulation with smaller step gives the optimum $R_{Load,N}$ =42 Ω.

**Amplifier test**

The differential class E amplifier is constructed using an EPC9051 development board. A photo of the configured amplifier is shown in figure 8. The component values are: $L_e$ = 568 nH (custom made air core), $C_{sh}$ = 200 pF (Vishay VJ0505 series), $L_{RFck}$: 47 µH (Coilcraft 1812PS). Although air core inductors are used in this test, suitable low profile ferrite inductors may be used.

AirFuel class 2 [3] standard specifies the reflected load reactance form -65j Ω to 5j Ω, or a relative range of 70j Ω. By impedance rotation on Smith Chart, we decided to perform the test from -30j Ω to +40j Ω instead. With the discrete programmable load [4], the amplifier is tested first without transmitting wireless power. The test stops when the device temperature reaches or exceeds 100°C or the drain voltage reaches or exceeds 82 V. Note that no heat sink is mounted and no forced air cooling is used. The measured total amplifier efficiency over the whole required impedance range is shown in figure 9. The measured gate drive power consumption is only 13 mW. The last data point at 65-30j Ω is not completed due to the temperature exceeding 100°C.

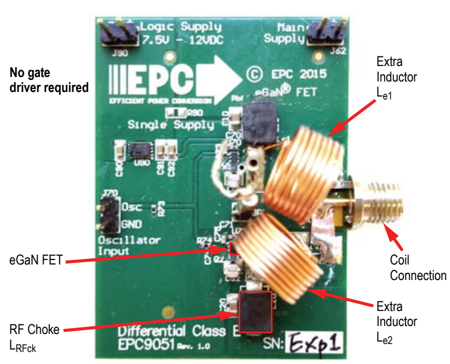


*Figure 8. Differential-mode class E configured EPC9051 development board*

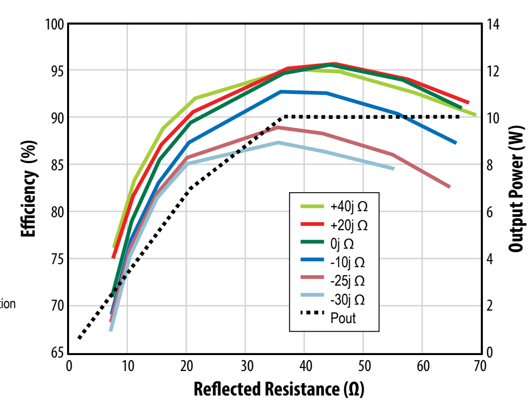


*Figure 9. Measured total amplifier efficiency including gate driver losses over the whole required impedance range*

**Wireless power transfer test**

Next, the amplifier is connected to a tuned class 2 coil and tested when transmitting wireless power. A photo of the test setup is shown in figure 10. Two different device coil orientations are considered as device location is not specified in the AirFuel standards. The distance between the source coil and the device coil is 9 mm.

Device orientation A is considered first. The total system efficiency including the rectifier loss on the device board is also measured for a range of output power at different tuned source coil reactance, as shown in figure 11. The maximum allowed DC load power is 6.5 W. The efficiency curves in figure 11 have very little spread with peak efficiency of 75%.

The total system efficiency for device orientation B is also measured, as shown in figure 12. The light load and peak efficiency for orientation B is slightly higher, but at high output power, the efficiency gets lower compared to orientation A. Example waveforms of source coil current and FET drain voltage are shown in figure 13.

**Comparison: differential class E vs. ZVS class D**

The total system efficiency of the class E amplifier (orientation A) is compared to that of the ZVS class D amplifier (EPC9114 with EPC9510 amplifier board) [6] at selected load reactances, shown in figure 14. The ZVS class D amplifier provides slightly higher peak efficiency, but it has wider efficiency spread. It can easily meet AirFuel class 2 standard, but it requires a half-bridge eGaN driver. Whereas the differential class E amplifier achieves 96% of the required impedance range.

**Summary**

In this application note, a differential class E amplifier suitable for a wireless power system is introduced. The basics of differential class E amplifier and the design procedure with EPC2037 [5] eGaN FETs are given, as well as test results for AirFuel class 2 compatibility.

With low gate charge and low input and output capacitances [7], eGaN FETs continues to improve performance, and even reduce cost in 6.78 MHz wireless power transfer applications.

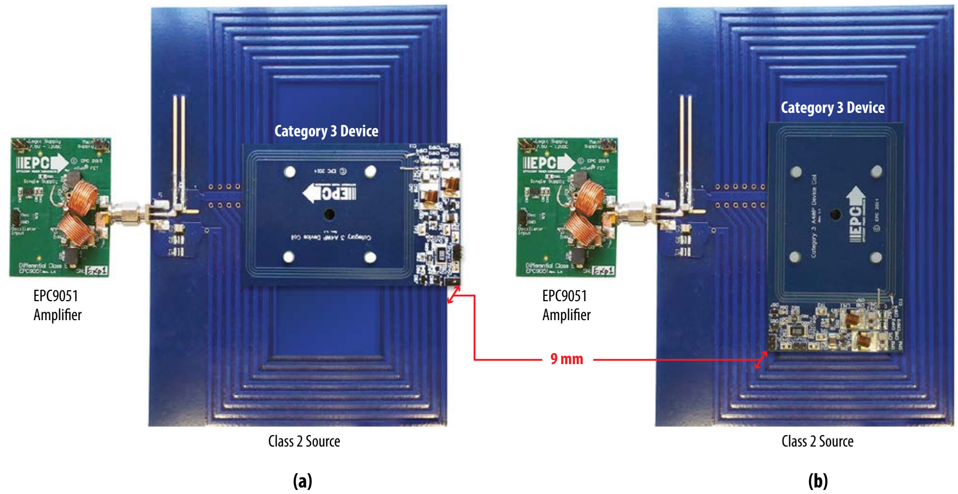


*Figure 10. System test setup for wireless power transfer: differential class E amplifier (EPC9051) with class 2 source coil and category 3 device coil. Two possible device coil orientations.*

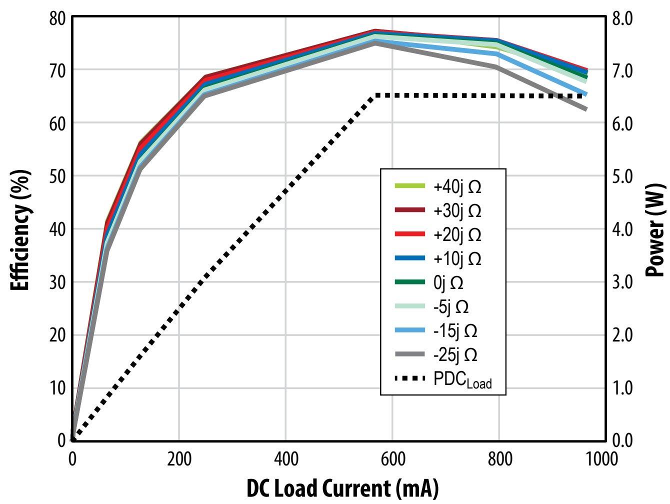


*Figure 11. Measured total system efficiency with a category 3 device. Orientation A*

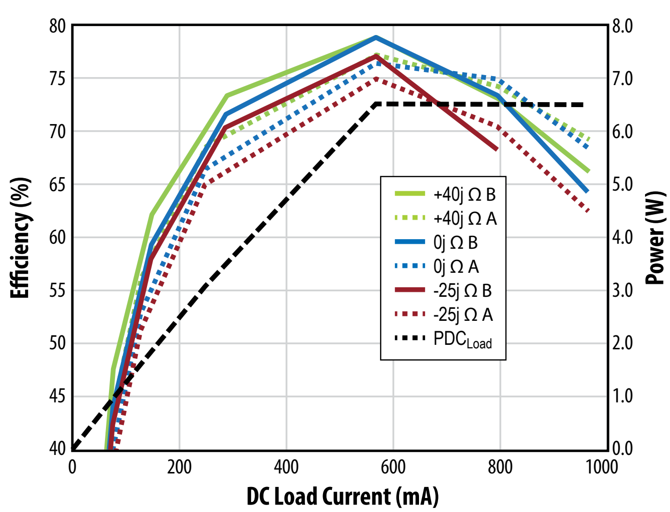


*Figure 12. Total system efficiency comparison between two possible device coil orientations*

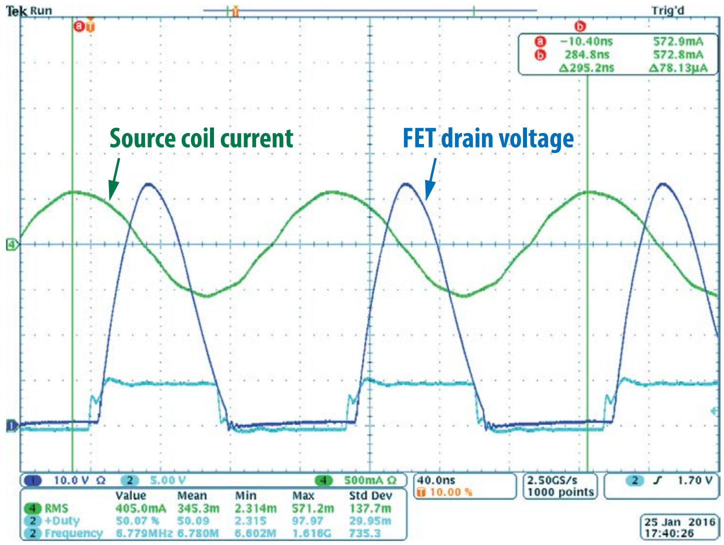


*Figure 13. Source coil current and FET drain voltage waveform of the differential class E amplifier. Operation conditions: device coil orientation A, source coil tuned to +20j Ω, 16.3 V input, 10 Ω DC load, 6.5 W DC output power, and 75% total system efficiency.*

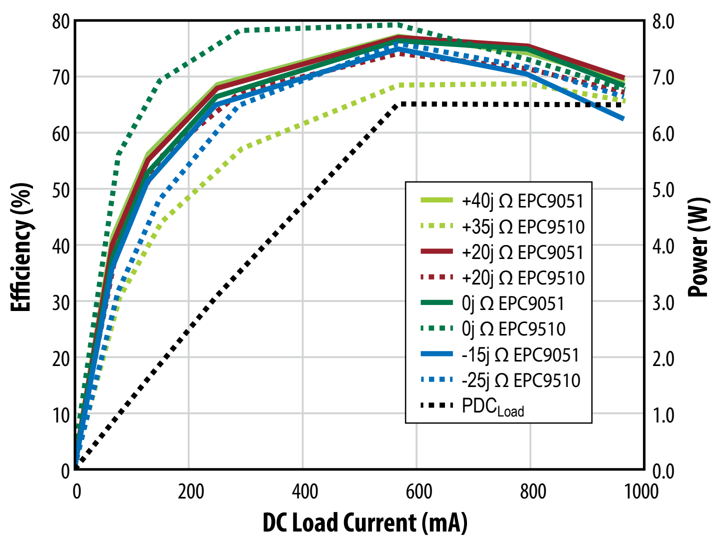


*Figure 14. Efficiency comparison of differential class E and ZVS class D amplifiers in wireless power systems.*

**References:**

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[2] M. Kazimierczuk, "*Collector amplitude modulation of the class E tuned power amplifier,*" IEEE Trans. Circuits Syst., vol. 31, no. 6, pp. 543-549, Jun. 1984.

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[4] M. A. de Rooij, *Wireless Power Handbook*, Second Edition, El Segundo, October 2015, ISBN 978-0-9966492-1-6.

[5] Efficient Power Conversion, "*EPC2037 – Enhancement Mode Power Transistor*," EPC2037 datasheet

[6] M. A. de Rooij, "*The ZVS Voltage-Mode Class-D amplifier, an eGaN® FET-enabled Topology for Highly Resonant Wireless Energy Transfer*," IEEE Applied Power Electronics Conference (APEC), March 2015.

[7] A. Lidow, J. Strydom, M. de Rooij, D. Reusch, *GaN Transistors for Efficient Power Conversion*, Second Edition, Chichester, United Kingdom, Wiley, ISBN 978-1-118-84476-2.