

A 10 W Multi-Mode Capable Wireless Power Amplifier for Mobile Devices

Michael de Rooij, Yuanzhe Zhang,

Efficient Power Conversion, 909 N. Sepulveda Blvd. ste230, El Segundo CA, 90245, U.S.A.,

Michael.derooij@epc-co.com, Yuanzhe.zhang@epc-co.com

Abstract

There are currently 3 wireless power standards for the mobile device market: the Wireless Power Consortium (Qi) standard [1], the Power Matters Alliance (PMA) standard [2] and the Alliance for Wireless Power (A4WP) standard [3]. Recently PMA and A4WP merged to become known as AirFuel™. The proliferation of wireless power products for mobile applications is leading to consumer confusion and hindering adoption of this technology [4]. A simple eGaN® integrated circuit based, single amplifier topology capable of operating to all of the mobile device wireless power standards is presented. It uses a modified ZVS class D amplifier topology capable of operating at both high (6.78 MHz) and low frequencies (100 kHz through 315 kHz). In addition, a specially designed source coil that can be used for all the wireless power standards is presented. The amplifier and source coil together allow for true multi-mode capable wireless power transfer that will be experimentally verified to both the AirFuel class 2 [5] and Qi/PMA [1, 2] standards and are designed for mobile phone charging applications.

1. Introduction

Wireless power applications continue to gain popularity as more products appear on the market based on one or more of the wireless power standards. Having multiple wireless power standards is not a good situation as it can lead to consumer confusion [4] regarding interoperability among the various wireless power devices. To simplify adoption, some manufacturers have begun offering multi-mode solutions that are compatible with two or more wireless standards [6]. The simplest solution is a multi-mode device (receiver) that can be used with any wireless standard source. This unfortunately increases the cost for the end user and due to the proliferation of single standard devices, is not a complete solution. Alternatively, the transmitting source can be made to support multiple wireless power standards. Typically multi-mode sources employ multiple amplifiers to drive various coils each to a specific standard. This solution adds significant complexity and cost to the source system, which can continue to hinder its adoption. A simple single amplifier solution is presented that can be used to drive a specially designed integrated multi-mode source coil that can operate to any of the mobile wireless power standards and overcome this issue.

2. Multi-mode capable wireless power system

A single amplifier multi-mode system comprises two major functional blocks, namely a multi-mode capable amplifier and a multi-mode capable source coil. The multi-mode source coil needs to be capable of operating at either high or low frequency to either of the standards without interfering with any of the other standards. In the case of AirFuel mode, the source needs to generate a uniform magnetic field across the charge surface. For Qi/PMA mode the magnetic flux needs to be concentrated around the magnetic coupling path. In addition, the source coil needs to be designed as a unique component and cannot simply be a sandwich of off-the-shelf coils. A top view and cross-section of the basic source coil structure is shown

in figure 1. Coil selectivity can be implemented by changing the frequency of the power source driving the coil using applicable tuning circuits similar to those proposed in [6]. However, due to the coupling between the coils in the composite structure, it is recommended to further increase the decoupling of the Qi/PMA coil from the AirFuel coil at high frequency using a parallel resonant circuit (L_{LF} and C_{LF}) shown in figure 1 (left).

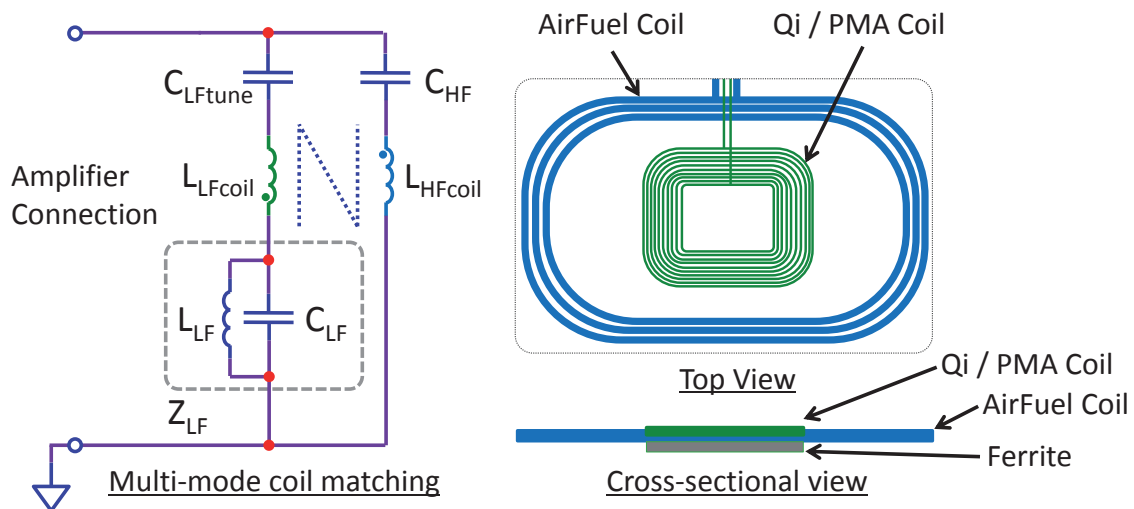


Fig. 1. Multi-mode coil structure and frequency selective tuning.

The new coil structure would need to be certified by all the standards bodies for which it is intended to be used.

2.1. Multi-mode source coil design

The NuCurrent PNC-21-T95L01E-130841R60 [7] source coil was selected for this project as it was specifically designed for a multi-mode wireless power system. The source coil comes equipped with one AirFuel coil, designed for 10 W class 2 operation, and one Qi/PMA coil designed to deliver 5 W into the load. The coil was fitted with an adapter board used for tuning the coils and for providing a connection to the amplifier.

Each mode of operation is to be tested with a corresponding device. The AirFuel mode uses an EPC 6.5 W category 3 device with series only tuning comprising 164 nH inductance and 266 pF capacitance. The Qi mode 5 W device uses a Würth Elektronik 760308102210 [8] coil series tuned with 112 nF and connected to a full bridge rectifier (same as the AirFuel device). The devices are placed 5 mm above the source coil. In AirFuel mode the device coupling is 27.9 % and in Qi mode the coupling is 38.0 %.

The Qi/PMA coil is connected in such a manner as to oppose the AirFuel mode field, which further helps to reduce the coupling between the source and device coils that favors loose coupling operation. The tuning board is configured in the manner shown in figure 1 where the high frequency decoupling tank was tuned with a 270 nH inductor and 1.068 nF capacitor.

3. Multi-mode wireless power capable amplifier topology

The ZVS class D amplifier has proven to be a simple, high efficiency solution for 6.78 MHz loosely coupled highly resonant wireless power applications [9, 10, 11, 12, 13, & 14]. The circuit that establishes ZVS for high frequency operation must be disconnected to allow the amplifier to operate at low frequency in hard switching mode without leading to over-current. eGaN FETs and integrated circuits have also proven to be efficient in the frequency range of

100 kHz through 315 kHz despite operating in hard switching mode [15]. Figure 2 shows the resultant multi-mode capable amplifier.

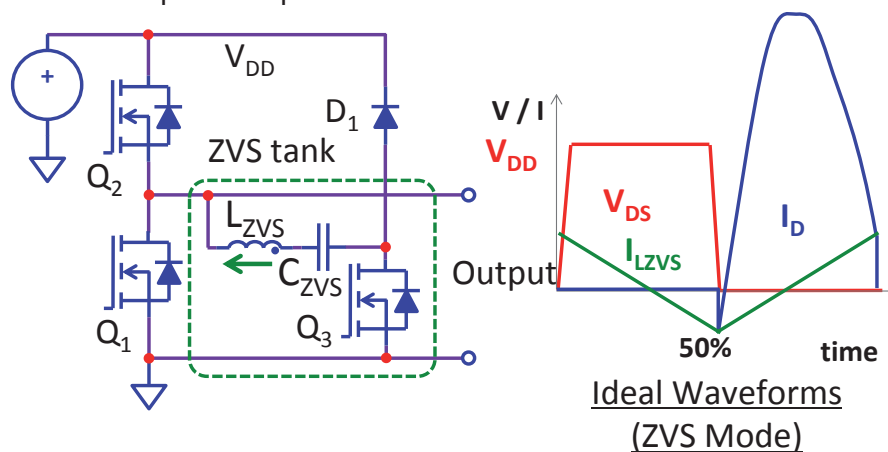


Fig. 2. Modified ZVS class D amplifier for multi-mode operation.

The disconnect function can be implemented using a low cost EPC2036 eGaN FET [16] that can be driven directly from logic to further keep costs low. Since the ZVS tank circuit can have current in it when the system is switched from AirFuel mode to Qi mode, it is recommended to include a clamp diode (D_1) to prevent overvoltage of the FET (Q_3). In this application, D_1 can be replaced by an eGaN FET with its gate shorted to its source using the same type of FET as Q_3 . It should be noted that the ZVS tank circuit disconnect function does not operate at high frequency and is only used to switch between operating modes.

4. Experimental Verification

A multi-mode capable system was built for experimental verification and was independently tested at 6.78 MHz to the AirFuel class 2 standard [5] and at 165 kHz in Qi mode based on the A6 standard [1].

4.1. Experimental Setup

The multi-mode wireless power system is shown in figure 3 and comprises an EPC9510 revision 2.01 multi-mode capable wireless power amplifier that uses the EPC2107 eGaN integrated circuit [17] and the NuCurrent PNC-21-T95L01E-130841R60 [7] multi-mode source coil fitted with an adapter board for tuning and connection to the amplifier. Also shown in figure 3 are an AirFuel category 3 compatible device and a Qi 5 W compatible device that uses a Würth Elektronik coil [8], with optimal operational position for each device on the source coil. Figure 3 also clearly shows a single connection to the amplifier for the source coil.

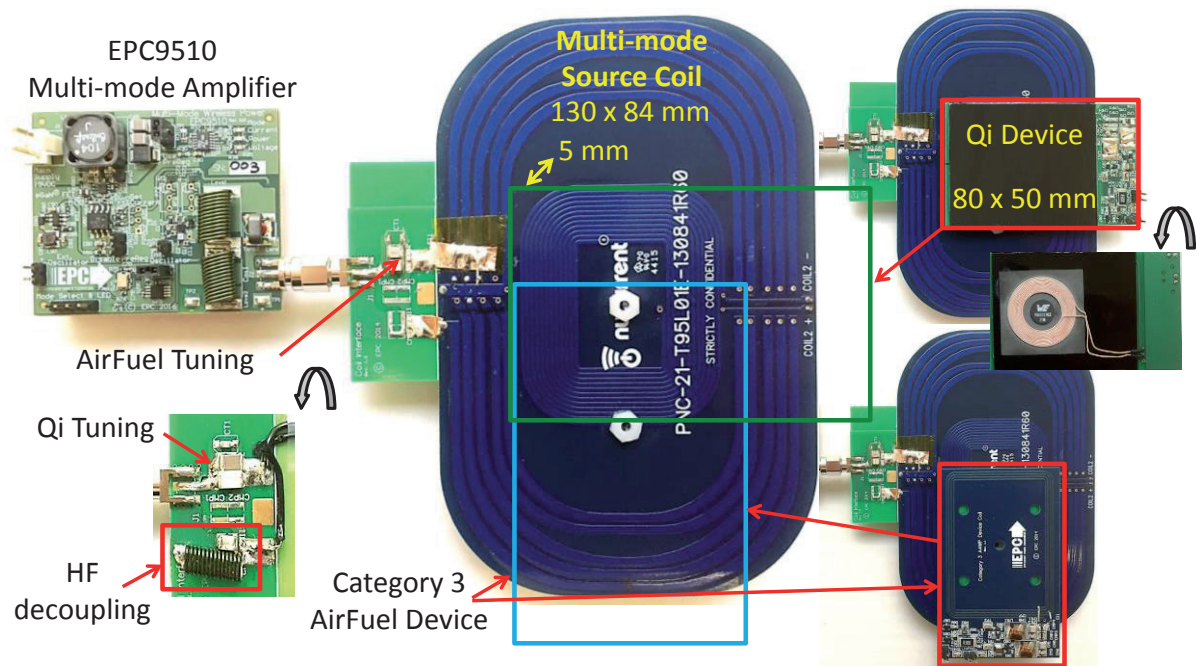


Fig. 3. The experimental multi-mode wireless power system showing the EPC9510 multi-mode amplifier (top left) with multi-mode source (center), Qi device (top right), AirFuel device (bottom right). Also shown are source coil tuning for AirFuel mode on the top side and Qi mode tuning on the bottom side with the optimal device placement locations for each of the devices.

The spacing between the top surface of the source coil and the bottom surface of the device coil was fixed at 5 mm. Additional tests were also performed with the spacing reduced to 3 mm. Testing requires that neither the eGaN IC's or gate driver's temperature exceeds 100°C, or that the voltage needed to drive the amplifier never exceeds 80 V.

4.2. Experimental Results

The system level DC input to DC output efficiency results are shown in figure 4 and include the gate driver operating power.

For AirFuel mode operation it can be seen from the results of figure 4 that the system is able to deliver power with reasonable efficiency that peaks at 75% and behaves in much the same manner as other AirFuel systems [9, 10, 12, & 14] when subjected to impedance variation that leads to variations in system efficiency. This compares well to the AirFuel only system reported in [10] where a peak efficiency of 80% was achieved. Due to the complex structure of the multi-mode source coil and the presence of the Qi/PMA coil and ferrite, additional impedance shifts were observed. This leads to shifts in power delivery based on the class 2 standard operating limits of either 580 mA_{RMS} coil current, 6.5 W load power limit or 10 W source power and is shown by the grey zone in figure 4.

System efficiency in Qi mode operation is lower than in AirFuel mode and is mainly due to the large distance between the source and device coils. The design of the ferrite on the bottom side of the coil is also not optimal, further contributing to low efficiency. The system however is still able to deliver the required power of 5 W.

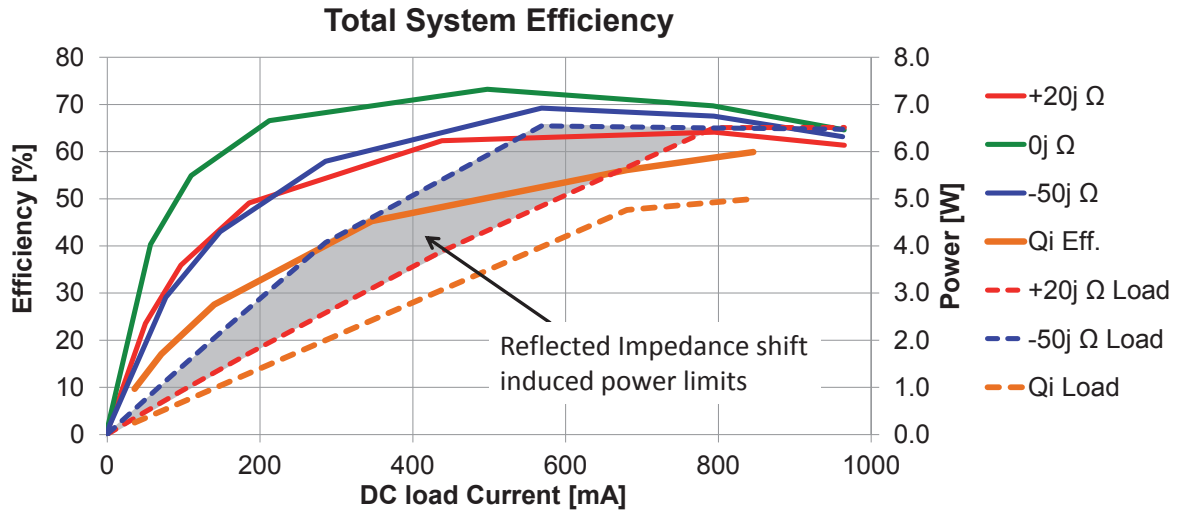


Fig. 4. Experimental DC input to DC output efficiency results for with the multi-mode system operating in either the AirFuel mode, tested to the class 2 standard, or the Qi mode tested based on the standard.

Due to the merging of conflicting requirements present in a multi-mode wireless power system, such as loose and tight coupling, additional tests were performed on the experimental system to determine the effect of coil separation on performance for each operating mode. Figure 5 shows the AirFuel mode system efficiency when the source coil is operated on-resonance for a coil separation of 3 mm and 5 mm. It should be noted that the efficiency results are barely distinguishable from each other but there is a shift in power delivery. This is due to the increase in reflected impedance for the same load variation with a 3 mm coil separation that allows for higher power delivery before the amplifier reaches its current limit.

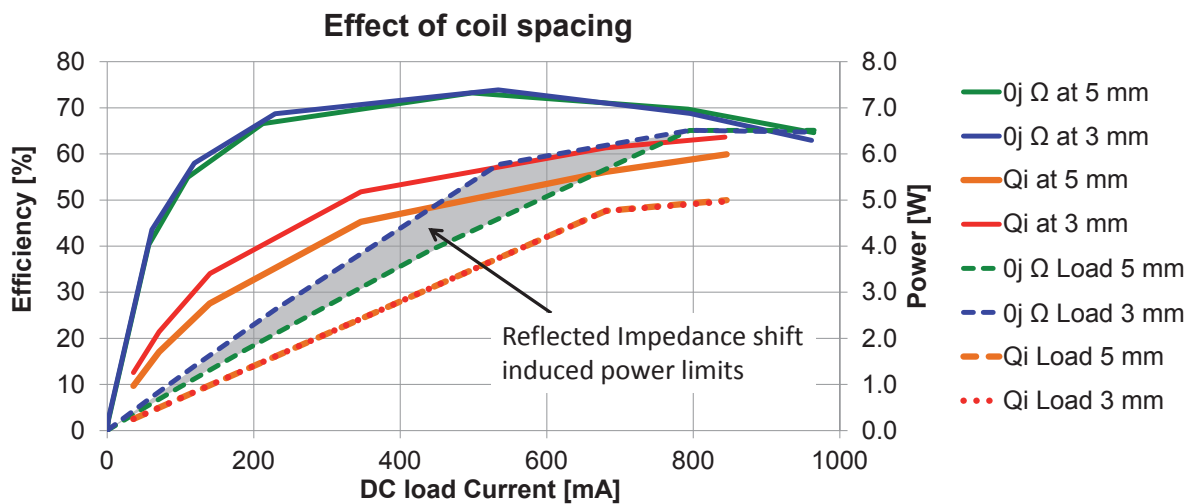


Fig. 5. Experimental DC input to DC output results for with the multi-mode system operating in either the AirFuel mode, tested to the class 2 standard, or the Qi mode tested based on the standard showing the effect of source coil to device coil 5 mm and 3 mm spacing on efficiency and power delivery.

In Qi mode the effect of coil separation is exactly the opposite where there is no change in power delivered but a noticeable improvement in system efficiency of approximately 5%. The lack of power shift is due to the device rectifier output voltage being fixed at 7 V (regulated)

by the source that defines the load power. The improvement in efficiency is due to the reduced separation that increases the coupling between the coils and reduces the required current to transfer power. Also notable is that the efficiency in Qi mode is never able to exceed that of the AirFuel mode.

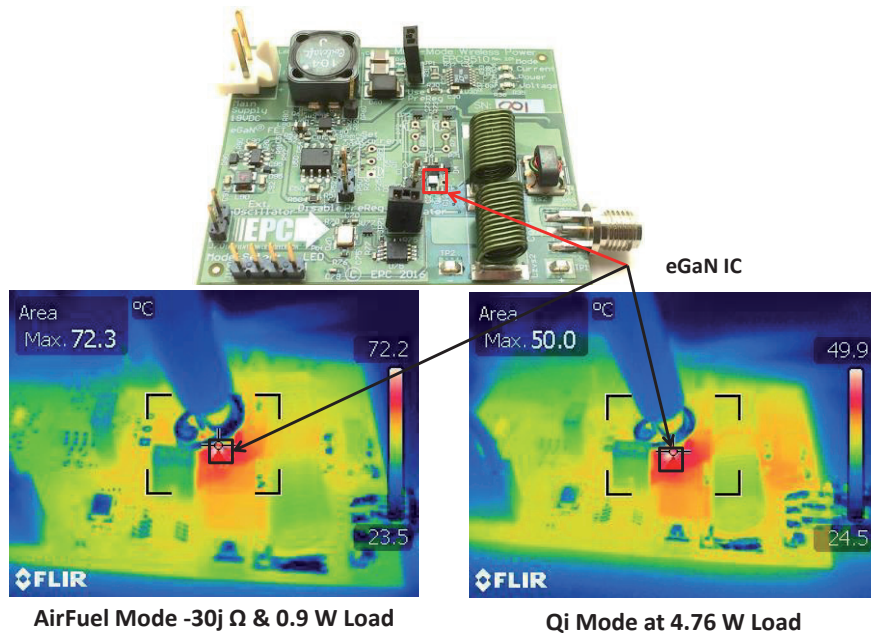


Fig. 6. Worst case thermal performance comparison between operating modes of the amplifier.

Figure 6 shows the thermal performance of the eGaN IC for the worst case under either operating mode without the use of a heatsink or forced air cooling. In the Qi case this is near maximum load power but for the AirFuel case it is where the reflected coil reactance is highly negative and the resistance component is low. The ZVS tank current under this load is completely cancelled by the coil current and the FETs inside the IC become hard switching. Increasing the magnitude of the negative reactance increases the supply voltage allowing the ZVS tank current to exceed the negative coil current thus regaining partial or even complete ZVS. Figure 6 reveals that operating temperature of the eGaN IC remains well below 75°C for all operating conditions in an ambient of 25°C.

Finally it should be noted that the multi-mode amplifier is required to operate with large differences in conditions for each mode. In the AirFuel mode the amplifier needs to be capable of delivering the required coil current of 580 mA_{RMS} where the supply voltage can vary from 2.7 V through 67 V. In Qi mode the source coil current is as high as 1.3 A_{RMS} but the supply voltage variation is small, ranging from 24.5 V to 29 V.

5. Conclusions

eGaN FETs and ICs have shown the ability to not only improve performance in wireless power applications, but can also bring about new ways of achieving multiple goals. In this paper a single amplifier, employing eGaN FETs and an eGaN integrated circuit, was experimentally verified to be capable of delivering wireless power while operating at high frequency to the AirFuel standard or at low frequency to the Qi/PMA standard. Testing reveals that the system is compatible with the AirFuel class 2 standard and is also capable of delivering the required power of 5 W in the Qi mode. To achieve this an integrated source coil was required that can be driven by a single amplifier. The challenging design also

highlighted the conflicting design requirements between the two competing wireless power standards namely the tight and loose coupling. In the case of the inductive wireless power approach, tight coupling with a short distance between the coils is required to achieve acceptable efficiencies. For highly resonant loose coupling systems a large spacing between the coils is desirable.

The ease of use and excellent performance capabilities of eGaN FETs and ICs allows designers to focus on the challenges of multi-mode systems such as coil design and tuning. eGaN FETs and ICs continue to change how power electronics systems are realized not only by improving performance, but also by enabling techniques not possible with MOSFETs. In this case a single amplifier multi-mode wireless power system can be realized and yields a significantly lower cost solution than a multiple amplifier solution based on MOSFETs.

6. References

- [1] "System Description Wireless Power Transfer," Vol. I: Low Power. Part 1: Interface Definition, Version 1.2, June 2015.
- [2] Power Matters Alliance. [Online] Available: www.powermatters.org
- [3] A4WP Wireless Power Transfer System Baseline System Specification (BSS), A4WP-S-0001 v1.3.1, February 25, 2015.
- [4] S. Sarah Underwood, "Multiple Standards Hinder Growth of Wireless Charging," Communications of the Association for Computing Machinery (CACM), September 2, 2014, [Online] Available: <http://cacm.acm.org/news/178234-multiple-standards-hinder-growth-of-wireless-charging/fulltext>
- [5] "A4WP PTU Resonator Class 2 Design - Spiral Type 140-90 Series (RES-14-0006)", A4WP standard document RES-14-0006 Ver. 1.2, June 26, 2014.
- [6] V. Muratov, "Multi-Mode Wireless Power Systems can be a Bridge to the Promised Land of Universal Contactless Charging," Wireless Power Summit, Berkeley CA, U.S.A., November 2014.
- [7] NuCurrent. coil part number PNC-21-T95L01E-130841R60, www.nucurrent.com
- [8] Würth Elektronik "WE-WPCC Wireless Power Charging Receiver Coil," 760308102210 datasheet [Online] Available: <http://katalog.we-online.com/pbs/datasheet/760308102210.pdf>
- [9] M. A. de Rooij, "Performance Comparison for A4WP Class-3 Wireless Power Compliance between eGaN® FET and MOSFET in a ZVS Class D Amplifier," International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management (PCIM - Europe), May 2015.
- [10] M. A. de Rooij, Wireless Power Handbook," Second Edition, El Segundo, October 2015, ISBN 978-0-9966492-1-6.

- [11] A. Lidow, J. Strydom, M. de Rooij, D. Reusch, “GaN Transistors for Efficient Power Conversion,” Second Edition, Wiley, ISBN 978-1-118-84476-2.
- [12] M. A. de Rooij, “eGaN® FET based Wireless Energy Transfer Topology Performance Comparisons,” International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management (PCIM - Europe), May 2014, pg. 610 – 617.
- [13] A. Lidow, M. A. de Rooij, “Performance Evaluation of Enhancement-Mode GaN transistors in Class-D and Class-E Wireless Power Transfer Systems,” Bodo Magazine, May 2014, pg. 56 – 60.
- [14] 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, pp 1608 - 1613.
- [15] D. Reusch, J. Strydom, and A. Lidow, “Highly Efficient Gallium Nitride Transistors Designed for High Power Density and High Output Current DC-DC Converters,” IEEE International Power Electronics and Application Conference (PEAC), pp.456-461, 2014.
- [16] Efficient Power Conversion, “EPC2036 – Enhancement Mode Power Transistor,” EPC2036 datasheet, April 2015, [Online] Available: <http://epc-co.com/epc/Products/eGaNfets/EPC2036.aspx>
- [17] Efficient Power Conversion Corporation, “Enhancement Mode Power Transistor,” EPC2107 datasheet, Jul. 2015 [Online] Available: http://epc-co.com/epc/documents/datasheets/EPC2107_datasheet.pdf