Automotive Compatible Single Amplifier Multi-mode Wireless Power for Mobile Devices

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***Abstract*—The proliferation of wireless power products for mobile applications is leading to consumer confusion and hindering adoption of this technology. A simple eGaN® FET based single amplifier topology capable of operating to all of the mobile device wireless power standards is presented. The high reliability of eGaN FETs further make this solution suitable for automotive applications. This paper presents the proposed topology with experimental verification that demonstrates excellent performance at both low frequencies (Qi & PMA standards) and high frequency (A4WP standard).**

***Keywords*—Wireless power, Multi-mode, Single amplifier**

I. 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 multi wireless power standards is not necessarily a good situation to have as it can lead to consumer confusion regarding interoperability between devices. Due to this some manufacturers have begun offering multi-mode solutions that are compatible with two or more wireless standards [1]. 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 source can be made to support multiple wireless power standards. Typically multi-mode sources employ multiple amplifiers to drive multiple coils each to a specific standard. This solution adds significant complexity and cost to the source system, which can significantly hinder its adoption. In this paper a simple single amplifier solution is presented that can be used to drive an integrated multi-mode coil that can operate to any of the mobile wireless power standards.

The proliferation of wireless power for mobile devices includes automotive applications. Early indications are that the automotive industry is set to adopt the tightly coupled WPC Qi standard [2, 3], a decision process that can take as long as three years. However, as additional wireless power products appear on the market based on the various wireless power standards, and the lengthy decision process for adoption by the automotive industry, the selection of the WPC Qi standard cannot be ruled as definitive. Multi-mode wireless power solutions may yet work their way into the automotive industry.

II. Multiple Wireless Power Standards

There are currently 3 wireless power standards for the mobile device market, namely; the Wireless Power Consortium (Qi) standard [3], the Power Matters Alliance (PMA) standard [4] and the Alliance for Wireless Power (rezence™) standard [5]. The major similarities and differences between these standards are given in table 1. Products based on all three of the standards are already in various design stages.

TABLE I. Comparison of the various wireless power standards

Standard	rezence Alliance for Wireless Power	pma Power Matters Alliance	Qi Wireless Power Consortium
Power	1 W – 70 W	5 W	5 W, 10 W
Placement	Any orientation, any placement	Specific placement	Specific placement
Multiple devices	Yes	No	No

Recently Joined rezence

III. Comparison between the various wireless power standards

To begin defining a multi-mode capable wireless power source system, the similarities and differences between them need to be understood. The goal is to ascertain if these similarities and differences can used to define a simple multi-mode capable system. Simplification is driven primarily by cost but it is also a matter of survival for wireless power in general as consumer confusion can ultimately hinder its adoption.

All the wireless system architectures are similar in structure comprising an amplifier, a coil-set and rectifier. The differences stem from operating frequency, rated load power, spatial requirements and control communications. The communications portion will not be covered in this paper as it can be integrated into the control IC and represents a fraction of the cost of the overall system cost. The main difference between the wireless power standards is the operating frequency, which will be strategically used in the multi-mode wireless power system design.

IV. A Multi-mode 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 [6, 7, & 8]. The basic power schematic is shown in fig. 1. As in the case of nearly all soft-switching converters, its operating frequency range is limited by the mechanism that establishes ZVS. This limitation will need to be overcome if the ZVS class D amplifier is to be used at a lower frequency such as that used by the Qi and PMA wireless power standards.

The ZVS class D amplifier is comprised of two FETs connected in a half bridge configuration and includes a ZVS tank circuit connected between the switch-node and ground to establish zero voltage switching. The ZVS tank circuit comprises an inductor L_{ZVS} and large capacitor C_{ZVS} that generates a current that can transition the C_{OSS} voltage from one state to the other. The question arises if this topology can be adapted to operate in the frequency range from 100 kHz through 315 kHz and also at 6.78 MHz and furthermore maintain high efficiency at all operating frequencies.

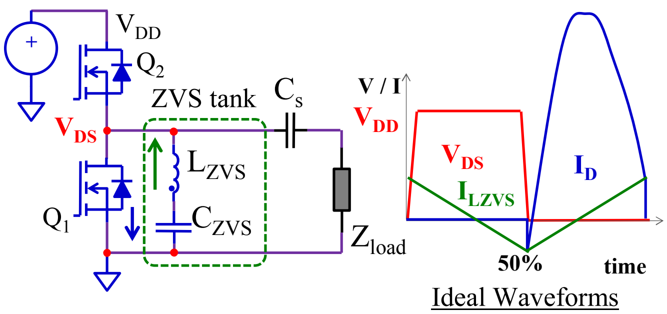

Fig. 1. ZVS Class D amplifier for high frequency operation.

At low frequency the current in the ZVS inductor (L_{ZVS}) when configured for high frequency operation, will become very high and render the circuit inoperable. A means is needed to disconnect the ZVS tank circuit for low frequency operation. Fig. 2 shows a small modification to the ZVS class D topology of fig. 1 that essentially disconnects the ZVS tank circuit for low frequency operation using one additional switch (Q_3). eGaN FETs have proven low loss operation in hard-switching applications even as high as 1 MHz [9]. When using eGaN FETs as the power switching devices in hard-switching mode of operation in the frequency range 100 kHz through 315 kHz, the converter is still expected to yield high efficiency.

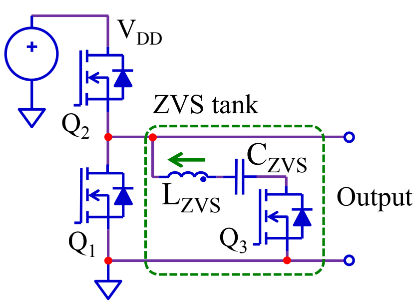

Fig. 2. Modified ZVS class D amplifier for multi-mode operation.

The modified ZVS class D of fig. 2 can now operate at both high and low frequencies. In both cases the output will be a square-wave voltage. Next the coils used to transfer the power need to be modified to operate under to the wireless power standards.

V. The Multi-Mode Source Coil Structure

The next major component in the multi-mode wireless power structure is the transmit coil. This component must be designed as a unique component and cannot simply be a sandwich of off the shelf coils. This is due to the order in which various components/materials of the independent structures will fall that will negatively impact the performance of others.

To begin, the loosely coupled coil sits at the bottom of the structure, with the tightly coupled coil on top. The ferrite of the tightly coupled coil is moved to below the loosely coupled coil to prevent shunting its magnetic field. A top view and cross-section of the basic structure is shown in fig. 3. The thickness of the loosely coupled coil is very thin so moving the ferrite structure down should have little impact on the operation of the Qi/PMA coil. Furthermore, the size of the ferrite is small and does not complete the magnetic field of the loosely coupled resonant system so that magnetic energy is primarily stored in the "air gap". Nonetheless, the selection of ferrite must still take the high frequency into consideration to keep losses in the ferrite volume down as much as possible.

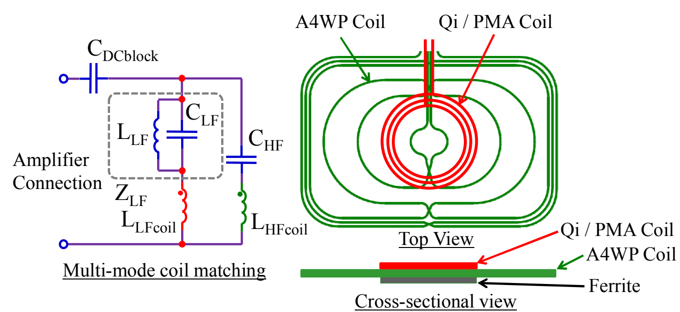

Fig. 3. Muli-mode coil structure and frequency selective matching.

Coil selectivity can be implemented by frequency selection using applicable matching circuits similar to those proposed in [1]. 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 A4WP coil at high frequency using a parallel resonant circuit (L_{LF} and C_{LF}) shown in fig. 3 (left). The selection of the inductance and capacitance values are not trivial and depend of the balance between the inductance magnitude and circulating current at 6.78 MHz in this tank circuit. A too low characteristic impedance will lead to high inductor current and high losses. A too high characteristic impedance will lead to a high inductance that will become a significant percentage of the low frequency coil inductance and low frequency operation will deteriorate with drop in system efficiency. A characteristic impedance value between 15 Ω and 20 Ω is recommended.

An analysis of the circuit for an A4WP Class-3 coil reveals that the high frequency capacitor (C_{HF}) will have an impedance exceeding 7 kΩ at 315 kHz, the worst case low frequency operation for this coil. The parallel tank circuit (L_{LF} and C_{LF}) will also have an impedance that exceeds 15 kΩ's if designed correctly at 6.78 MHz. This yields currents in each of the coils for the non-operating frequency in the very low milli-amps.

VI. Wireless power for automotive applications

Reliability is an important factor for automotive applications and the Automotive Electronics Council (AEC) Component Technical Committee has developed a set of test conditions to establish a common understanding of "Automotive worthy or capable" components in relation to robustness and reliability profiles. AEC-Q101 Rev D1 [10] defines the test conditions and goals for discrete semiconductors under which eGaN FETs will fall.

The reliability of eGaN FETs presented in [11] have indicated very high reliability when tested to various JEDEC and MIL standards. Once a final design for the multi-mode amplifier has been made, then the applicable eGaN FETs can be qualified to the AEC-Q101 automotive standard [2, 10]. Taking advantage of newer technologies that enable new design options to support competitive features often poses a challenge since meeting the AEQ specifications takes time, financial investment and, at times, the need for an update in the specification to address new materials characteristics.

For automotive applications, and in particular for an A4WP based system, the confined areas within a vehicle targeted for wireless power, such as the center console, offer opportunities for use case coil impedance range reduction. This is important as it simplifies the design of the amplifier. eGaN FETs have proven capable of driving an impedance range of 1.2 Ω -35j Ω through 56 Ω + 35j Ω to the A4WP Class-3 standard without the need for adaptive tuning techniques [6] using a single ended ZVS class D topology. In differential mode the estimated amplifier impedance drive range increases to ±50j Ω.

The advent of multiple wireless power standard receivers means that automotive solutions will need to support them all in order to satisfy the needs of the customer or risk losing some specifically looking for a wireless power feature. Given the automotive reliability requirements and the complexity of supporting multiple standards, a single amplifier will address this issue both by component count and complexity reduction. Using a single power amplifier that can support all the wireless power operating conditions will be experimentally demonstrated in the next section.

VII. Experimental

Due to the absence of an actual integrated coil for experimentation, the focus of testing will be on the ability of the amplifier to operate to all the wireless power standards and in particular at the two main frequencies of 300 kHz and 6.78 MHz.

The performance of the ZVS class D amplifier operating to the A4WP Class-3 standard at 6.78 MHz has been reported in [6, 7] using the EPC9919 Rev. 2.0 amplifier fitted with EPC8010 [12] devices that includes a synchronous bootstrap FET circuit that eliminated gate driver induced bootstrap diode Q_{RR} losses. This amplifier was configured as single ended. For testing a calibrated load was specially constructed to provide the exact conditions necessary to test to the A4WP standard and to further determine the AC power delivered to the load under variable load impedance conditions. The measured impedance of the calibrated load is shown in fig. 4 and included power instrumentation such as current probe.

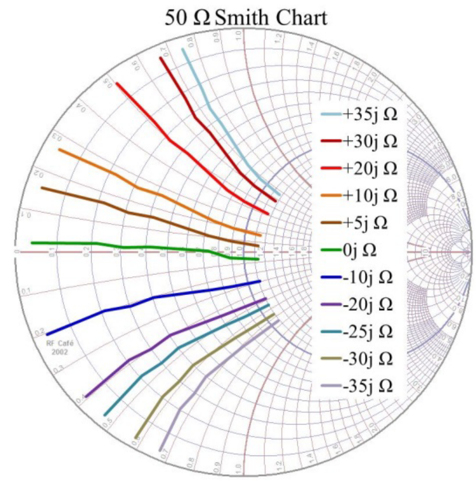

Fig. 4. Measured impedance of a special load used for testing the amplifier to the A4WP Class-3 standard.

Two coils [13] made by Vishay in accordance to the Wireless Power Consortium (WPC-Qi) [3] standard were assembled to form a closed system as shown in fig. 5. This coil-set was used to test the ability of the amplifier to drive the low frequency coil up to its maximum rating of 5 W. A full bridge schottky diode rectifier was used to rectify the high frequency (300 kHz) voltage to DC. The source coil was simply connected to the output of the amplifier. In this experimental setup the new EPC9509 differential mode wireless power amplifier, fitted with the EPC2108 [14] integrated FET, was used to drive the coil in bypass mode (without the on-board controller) and in differential mode. In addition, the ZVS tank circuit was disconnect to allow the amplifier to operate in hard-switching mode. The switching frequency was selected to be 300 kHz as this represents the worst case scenario for a hard-switching converter.

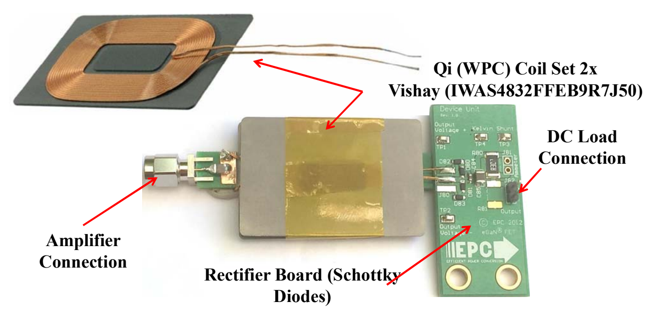

Fig. 5. Experimental Qi/PMA based coil setup (Vishay coil-set) used to test the low frequency performance of the amplifier attached to a rectifier board.

VIII. Experimental results

Testing to the A4WP standard revealed that the MOSFET version of the amplifier was found to be A4WP Class-3 compliant over the imaginary impedance range of -30j Ω though +20j Ω whereas the eGaN FET version of the amplifier was found to be A4WP Class-3 compliant over the imaginary impedance range of -35j Ω though +35j Ω, a relative difference of 20j Ω. At ±35j Ω the required voltage for the amplifier to drive the coil reached 80 V and is the only limiting factor for the eGaN FET amplifier. In the case of the MOSFET amplifier the gate driver or device temperature exceeding 100°C were the limiting factors.

Fig. 6 shows the measured total amplifier losses, including the gate driver, as function of imaginary load impedance for various load resistances. The higher the load resistance became the greater the performance benefit the eGaN FET version of the amplifier had over the MOSFET version.

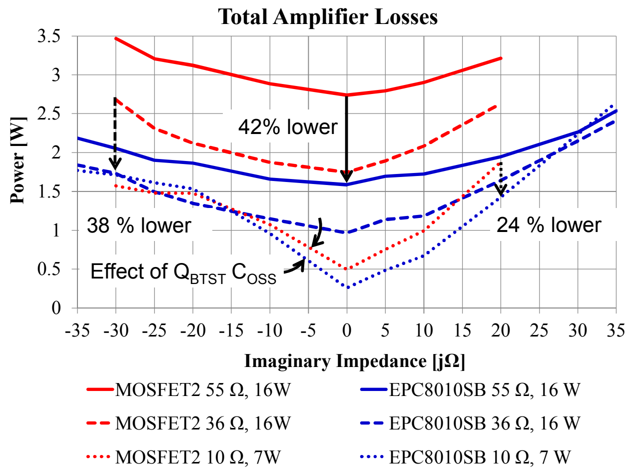

Fig. 6. Experimental performance comparison between MOSFET (red) and eGaN FET (blue) total amplifier losses operating at 6.78 MHz delivering power to a class 3 A4WP load as function of imaginary load impedance for various real load impedances.

The system efficiency (DC power in to DC power out) is shown in fig. 7 using the EPC9509 amplifier with disconnected ZVS tank circuits in differential mode driving the Qi based Vishay coil-set. It is notable that the efficiency of the system does not exceed 80 % and is primarily driven by the coil set. This is evident when analyzing the losses in the system. Experimentally, shown in fig. 8 is the thermal performance of the amplifier and rectifier operating at 300 kHz and delivering 5 W load power. It can be seen that the gate driver is the hottest component at 10°C rise and that the eGaN FETs [14] does not show up in the thermal image. On the rectifier side the schottky diodes are the hottest components with a temperature rise of 25°C. These results clearly show that the performance of the low frequency system is dominated by the coil-set.

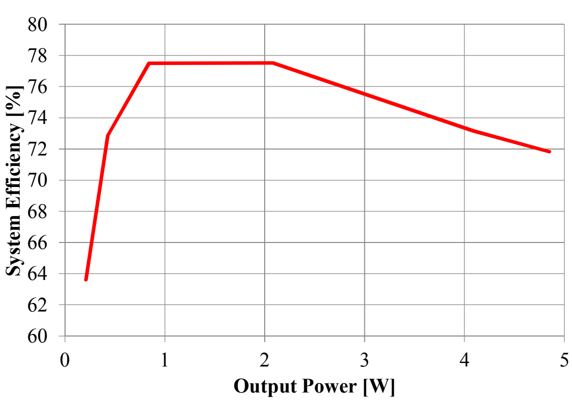

Fig. 7. System efficiency results as function of output power when the amplifier is operating hard-switching and using the Vishay-coil set.

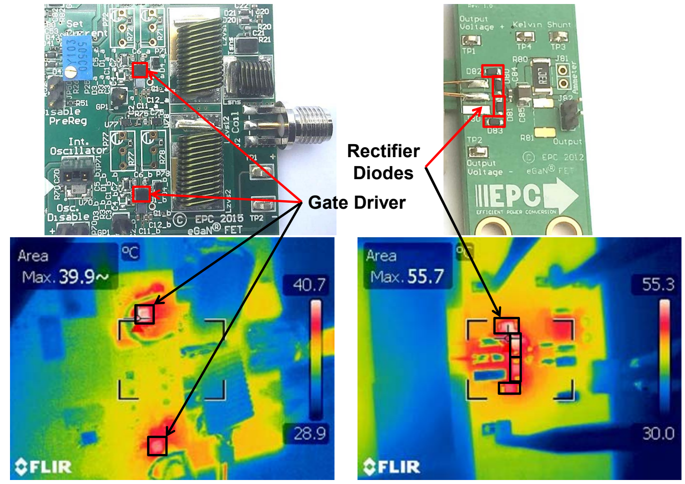

Fig. 8. Experimental thermal performance of the amplifier using the Vishay coil-set, hard-switching, operating at 300 kHz and delivering 5 W load power and ambient temperature of 30°C.

IX. Conclusions

An experimental evaluation of an eGaN FET based ZVS class D amplifier that is capable of driving any wireless power standard coil-set was presented. This was possible with a small modification to the amplifier circuit by effectively disconnecting the ZVS tank for low frequency operation.

In the case of the A4WP standard operating at 6.78 MHz, the eGaN FET was able to drive a substantially wider impedance range than a comparable MOSFET. This helps to contain costs in adaptive matching networks. Furthermore, the higher performance of the eGaN FETs resulted in lower heat generation which did not require any heat-sinking or forced air cooling that leads to more cost savings and higher reliability than MOSFETs.

The lower C_{OSS} of the eGaN FET relative to an equivalent MOSFET ensures a lower loss amplifier is possible, even when the devices are hard-switching, such as driving a coil-set to the Qi/PMA standards. It was experimentally demonstrated that at 5 W load power and 300 kHz operation, the eGaN FETs did not show up on the thermal image relative to the immediate background and that the system efficiency was dominated by the coil-set efficiency.

For automotive applications reliability is a key factor and eGaN FETs have been proven highly reliable through many device hours of testing. In the case of automotive wireless power applications, where the use case is restricted, opportunities arise to reduce wireless power specifications such the load impedance range to help simplify the design of such systems and contain costs. Using eGaN FET, further help as the wider impedance drive range and ability to design a single amplifier that can be used for any wireless power standard all contribute to cost and system complexity reduction, all critical components for automotive acceptance.

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