eGaN® FETs in Low Power Wireless Energy Converters

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Wireless power applications are gaining popularity in many commodity products such as mobile phone chargers. Most of the wireless power solutions have focused on tight coupling with induction coil solutions at operating frequencies around 200 kHz, and Class E, F and S amplifier converter topologies. Recently, however, there has been a push for operation in the restricted and unlicensed lower ISM band at 6.78 MHz where traditional MOSFET technology is approaching its capability limit. Enhancement mode gallium nitride transistors offer an alternative to MOSFETs as they can switch fast enough to be ideal for wireless power applications. This paper will focus on the experimental evaluation of an induction coil wireless energy system using Efficient Power Conversion's (EPC) eGaN FETs in a half bridge topology operating at 6.78 MHz designed to be suitable for multiple 5 W USB based charging loads.

Induction Wireless Energy System Overview

An induction wireless energy system comprises 4 main sections:

1. An amplifier (a.k.a. a power converter).
2. A transmit coil including matching network.
3. A receive coil including matching network.
4. A rectifier with high frequency filtering.

To understand and design a wireless energy system, one must first understand the basic principle of operation of the transmit and receive induction coils.

The transmit coil is connected to a high frequency AC source such that it will generate a magnetic field that can couple to the receive coil, thereby transferring the energy. The induction coil set can be represented by a transformer circuit model with a high leakage inductance. Figure 1 shows the simplified schematic model for this transformer where L_{mx} represents the magnetizing inductance and L_{rx} represents the leakage inductance. Analysis of this model reveals that the ability to efficiently transfer power to the secondary is almost entirely determined by the primary side leakage inductance (1). The high value of the leakage inductance in such systems, typically of the same magnitude as the magnetizing inductance, reduces the current in the primary circuit and thus the voltage across the ideal transformer primary winding. The leakage inductance is approximately inversely proportional to the distance between the coils. The exact relationship between leakage inductance and distance between the coils falls outside the scope of this article, however, a coupling coefficient around 0.12 will be used in the design and discussion.

Operating the induction coils at resonance using external components significantly improves the transfer of power by increasing the voltage to the ideal transformer primary winding. This can be achieved by adding tuned matching networks to both the transmit and receive coils (1).

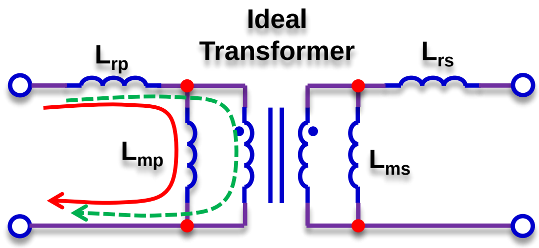

Figure 1. Equivalent circuit model for the induction coils.

Operation in the ISM band at 6.78 MHz requires an air core transformer as magnetic material losses would otherwise become significant. An air core transformer will have very low magnetizing inductance and hence requires higher currents to operate.

Given the need to operate at resonance and the transformer inductance values driven by the application, a matching network is required. This matching network will transform the impedance of the power stage to the transformer for maximum energy transfer, and will also be used to tune the resonant frequency of the coils to the desired frequency.

The induction coils used in this demonstration was designed and supplied by WiTricty Corp. (2).

The Power Amplifier

Before selecting a power amplifier, one must first determine the main operating specifications, such as supply voltage and load power, as these will impact the choice of power topology. The goal is to design a system with the highest possible operating efficiency across the load variation.

It was decided to evaluate a system that could operate up to 24 V to determine how much power could efficiently be transferred in a high frequency wireless system. Most USB applications are limited to 5 W, but market trends indicate that multiple loads driven by a single source are desired, which drives higher output power capability. Excluded in the demonstration is secondary regulation for the output to maintain 5 V regardless of load. Also excluded are the complexities of providing communications between the device and source modules for enhanced control and foreign metal object detection (FMOD) typical of wireless power systems.

Switching-based converters are required for wireless power applications because classic RF amplifiers do not have sufficient conversion efficiency to make them practical choices. This reduces the number of suitable converter choices for high efficiency wireless energy applications to Class D, Class E & F (3) and Class S configurations (4). To further add constraints, operation in the ISM band at 6.78 MHz (5) is restricted to ±15 kHz bandwidth which essentially eliminates frequency modulation techniques for output regulation (voltage or load). Class E and F converters have the disadvantage that the main switch must be capable of blocking the full coil voltage whereas for Class D and

S converters the switches only need to be able to block the supply voltage. Furthermore, class E and F converters are harder to control in applications where timing for ZVS operation is difficult to determine as the switch forms part of the resonant circuit. In the case of a class S amplifier, control requires a larger bandwidth than is permitted for use in the ISM band.

The logical amplifier selected was therefore a Class D converter operating at a fixed frequency. Duty cycle modulation will have little effect on output regulation if it is kept within ±10% of 50% duty cycle as the induction coils will be operating at resonance (The main effect of duty cycle will be to affect the efficiency of the converter outside the ±10% limits and will introduce current harmonics into the coil due to the spectral content of the source that may exceed the ISM band limits).

The power amplifier chosen for evaluation was a half bridge selected because eGaN FETs operate more efficiently at a higher voltage and a high performance gate driver is available (6) to keep costs down.

The converter is operated above resonance to take advantage of zero voltage switching (ZVS) and therefore obtain maximum power amplifier efficiency. The smallest 40 V eGaN FET, EPC2014 (7), was chosen because it has a low on-state resistance and low C_{oss}, all factors that will ensure minimum losses. Figure 2 shows a block diagram of the wireless system.

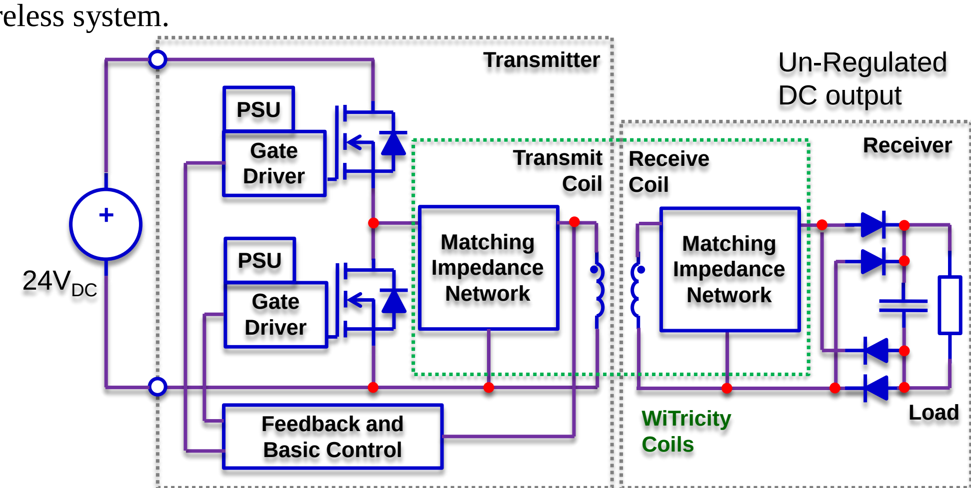

Figure 2. Schematic Block diagram of the proposed wireless energy system.

Output Regulation and Control

There are 2 control methods used in wireless power converters:

1) Constant bus voltage - varying frequency control
2) Constant frequency - varying bus voltage control

Constant bus voltage - varying frequency control. This is the most popular method of control for wireless converters that typically operate in the 100 kHz to 200 kHz range and is popular for wireless converters because it results in a power converter with fewer components. However, it requires some form of feedback over the separation barrier for moderate control of the output. The traditional solution has been to use a form of digital communications protocol based on the wireless standard (8). This offers a slow yet reasonable system for control.

The main drawbacks of this method are:

1) The communications between the device and source unit is superimposed on the power and can cause some perturbations in power. This may cause the system to not always operate at peak efficiency.
2) The system control will vary the operating frequency to control the output based on load demand. When operating in the ISM band, this cannot exceed the maximum bandwidth of ±15 kHz, and therefore consumes any tolerances in the coil design.

Enhanced output voltage regulation is achieved by adding a high performance buck regulator.

Constant frequency - varying bus voltage control. This is an alternative method of control for a wireless system as it requires an additional front end converter to regulate the DC supply voltage to the power amplifier. The power amplifier, induction coil set and rectifier operate as a DC transformer. Additional regulation is still required on the output as the rectifier load will need to be operated as a constant resistor load to ensure maximum operating efficiency across the load range. This method allows very tight control of the operating frequency thereby meeting the strict ISM bandwidth requirements.

There are three types of wireless systems; tightly coupled (source and receive coils are very close physically and the magnetic fields centered), loosely coupled (source and receive coils are relatively close physically to each other but not necessarily touching, and the magnetic fields centered) and, flexibly coupled (the distance between the source and receive coils and the magnetic field centers can vary). Excluded from this method of control are the effects of varying distance and alignment between the source and device coils which will impact the coupling factor and hence the leakage inductance values of the equivalent circuit model transformer. This will result in a shift of the resonant frequency of the coil. Methods to align and fix the distance between the coils are therefore highly recommended.

The Rectifier

The function of the rectifier is to convert the high frequency AC of the receive coil to a DC voltage. Important considerations for the rectifier include conduction and switching losses. For the discussion in this article the rectifier will be limited to a simple full wave diode bridge. Synchronous rectification is possible, but requires additional consideration to correctly implement given the critical timing needs when using eGaN FETs, and falls outside the scope of this article.

Power Loss Considerations

The high frequency operation of the power amplifier means higher operating losses. It is preferable to operate the converter with zero voltage switching (ZVS) as this will yield maximum efficiency by eliminating C_{oss} based losses. Determination of losses for each component in the circuit requires knowledge of how the circuit operates. The major loss contributors in the system are:

- The switching FETs including gate driver power consumption
- The rectifier diodes
- The induction coil set including the matching networks

Switching FET Losses. Losses in both the upper and lower FETs are the identical as the induction coil current only has an AC component. The loss breakdown for the FETs can be divided as follows:

- *Conduction losses ($I^2 \cdot R$):* Present in both the upper and lower FETs. Calculations need to account for the $R_{DS(ON)}$ at elevated temperature. The conduction losses in the FET can be calculated using the following equation (derived based on the operation of the converter and assumes a sinusoidal fundamental current):
$$P_{cond} = \tfrac{1}{4} \cdot \pi \cdot I_{coilpk}^2 \cdot R_{DS(ON)} \qquad [1]$$
Where I_{coilpk} is the peak of the coil current.
- *Switching losses:* The converter operates with ZVS at turn-on, but not turn-off, therefore the turn-off switching losses need to be determined using the following equation:
$$P_{sw} = V_{sup} \cdot I_{off} \cdot t_{sw} \cdot f \qquad [2]$$
Where V_{sup} is the supply voltage to the converter, I_{off} is the current at the time of turn-off, t_{sw} is the switching time and f is the operating frequency.

An analysis of the losses in the power amplifier show that the losses in each of the FETs are higher than what can be efficiently cooled using only a PCB. As a result, augmented cooling must be provided. The addition of a small heat-sink mounted on top of the FETs can significantly improve cooling of the FETs as demonstrated in (9).

Gate Driver Power Consumption. Gate driver power consumption also needs to be added to the power loss equation of the FETs as operation in the multi-MHz region will cause these losses to be significant. Gate driver power consumption comprises both quiescent and operation power consumption. The latter is proportional to operating frequency and gate charge of the FETs.

The energy consumption in the gate can be determined using the following equation:
$$P_{gate} = C_{iss} \cdot V_{GS}^2 \cdot f \text{ (per FET).} \qquad [3]$$
The gate charge power can then be added to the quiescent power consumption. Additional losses in the gate driver resistances will also need to be determined.

Rectifier Power Losses. The output full bridge rectifier is comprised of Schottky diodes with zero recovery losses. The loss breakdowns for the diodes reduce to:

- *Conduction losses ($2 \cdot V_f \cdot I_{avg}$ – for all 4 diodes):* The average diode current needs to be determined, however since it is primarily sinusoidal the following approximation will suffice:
$$I_{avg} = (2/\pi) \cdot I_{pk} \qquad [4]$$
Where I_{pk} is the peak of the sine current.
- *Capacitive losses ($\tfrac{1}{2} \cdot C_T \cdot V_R^2 \cdot f$ – per diode):* V_R is the output DC voltage and C_T is the average capacitance of the diode for the output voltage. The average capacitance of the diode needs to be determined for the blocking voltage by

integration of the non-linear capacitance voltage curve and dividing by the operating voltage.

Induction Coil Set Losses. The induction coil set also has losses which contribute to a significant portion of the overall system efficiency. Coil losses are driven primarily by winding resistance which is dominated by skin and proximity effects, and matching network losses. The detailed analysis of the coils by WiTricity (2) has produced accurate values of equivalent resistance in both transmit and receive coils that can be used to determine the losses based on the current in the coils. Once the current flowing in the coils has been determined, the losses can be calculated using the following equation:

$$P_{coil} = I_{coil}^2 \cdot R_{coil} \quad [5]$$

The current in the coils must be sinusoidal (required by FCC for compliance in the ISM band) making it easy to calculate the losses. The power losses in each coil must be calculated separately as the currents are not the same. For the coils provided by WiTricity, the primary winding has a resistance at 6.78 MHz of 520 mΩ, and the secondary winding a resistance of 335 mΩ.

Experimental Validation

Using coils with matching networks supplied by WiTricity Corp (2), a demonstration unit was built to evaluate the performance of the eGaN FETs.

The physical design of the circuit requires special attention to layout due to the high switching frequency of the converter and the rapid transitions in voltage and currents that can be present. The small size of the power circuit components makes measurements of critical nodes difficult, and therefore probes that allow improved connection to oscilloscope probes were embedded into the PCB.

The experimental unit was designed as four separate circuit boards:

1. A source unit (power amplifier)
2. A source coil
3. A device coil
4. A device unit (rectifier)

The source unit contains the power amplifier (switching converter), gate driver, supply regulators and a phase follower controller. Voltage of the source coil is fed back using a co-axial cable connection where it is converted into a square wave voltage. This square wave voltage is then delayed and timed before being used to drive the gate driver, producing a quasi-self-oscillating feedback controller for the system. This allows for very precise tuning of frequency, duty cycle, and dead-timing for each of the FETs. Figure 3 shows a photo of the full wireless energy system setup. 50 Ω SMA connectors were used to connect each of the boards together and 1 inch long nylon stand-offs were used to separate the source and device coils. The source coil feedback voltage connection made use of SMB snap in connectors.

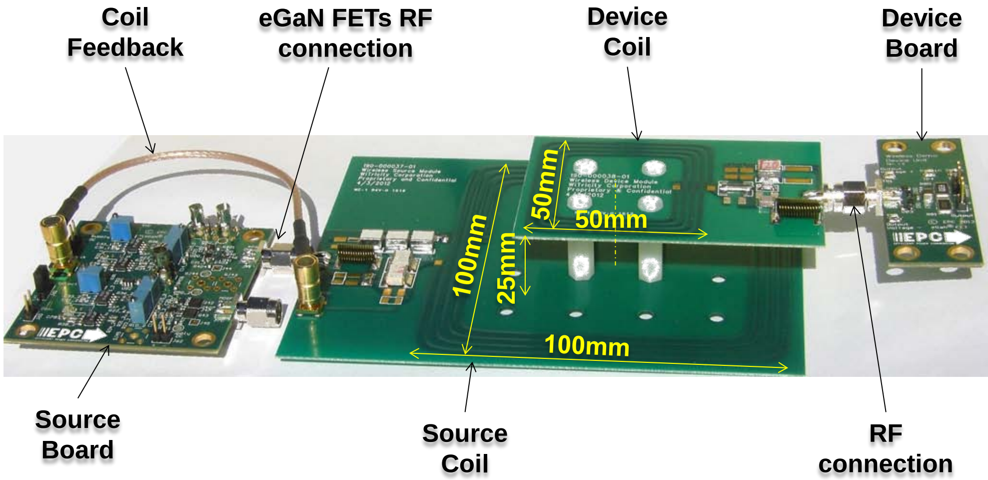

Figure 3. Photo of the wireless energy system co-developed by EPC and WiTricty used for experimentation.

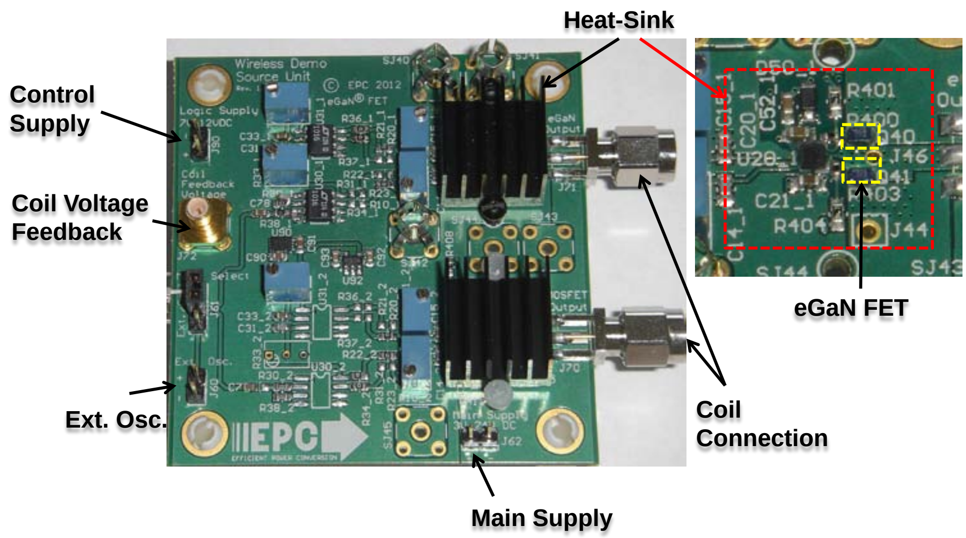

Figure 4. Photo of the EPC source board showing the various main components and sub-sections.

A 15 mm by 15 mm by 14.5 mm high heat-sink made by Advanced Thermal Solutions (10) was mounted flat on top of the eGaN FETs using a thin sheet of Wakefield thermal interface material number 173 (11). Figure 4 is a photo of the source board with the heat-sink mounted for enhanced cooling of the eGaN FETs.

The LM5113 half bridge eGaN FET gate driver from Texas Instruments(6) was used to drive the eGaN FETs. The small 2 mm x 2 mm BGA was selected for compactness. It is important to note that the LM5113 IC in this application is being operated well beyond its design frequency limit of approximately 5 MHz. The LM5113 logic circuits are capable of very high switching frequencies but the internal bootstrap power supply requires a minimum low-side on-time of approximately100 ns to charge the high side supply to the required voltage. As a result an additional external bootstrap power supply was added to the LM5113 circuit followed by a LDO regulator to ensure 5 V on the upper FET circuit. The high switching frequency also meant that the LM5113 would dissipate significant power and as such was therefore placed under the heat-sink for additional cooling.

Figure 5 shows a close-up photo of the device board with embedded shunt and minimum load for evaluation. Embedded Kelvin connections were used for accurate current and voltage measurements.

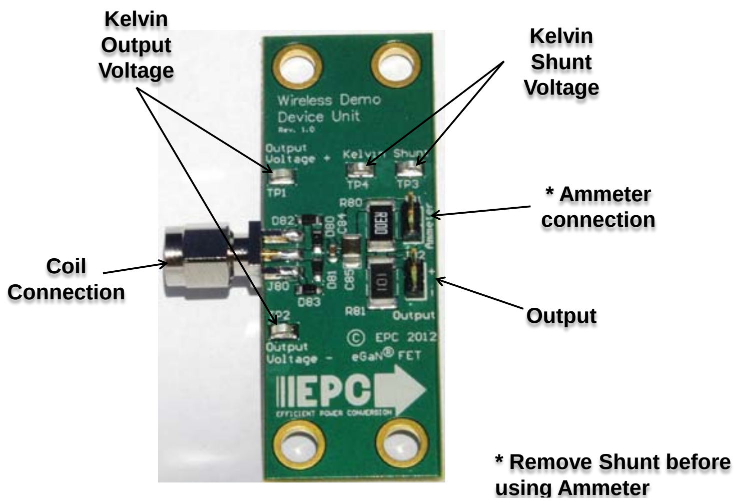

Figure 5. Photo of the EPC device board showing the various main components.

Experimental Results

Initial testing determined the optimal operating frequency for the coil set given various DC load resistances. Figure 6 shows the efficiency of the wireless converter system operating at peak efficiency for various loads (Note that each trace on the graph also represents a different operating frequency). Measurements of efficiency as function of load power were then taken by varying the DC supply voltage to the power amplifier and exclude gate driver power consumption. The load resistance variation shown is in the range of 2:1.

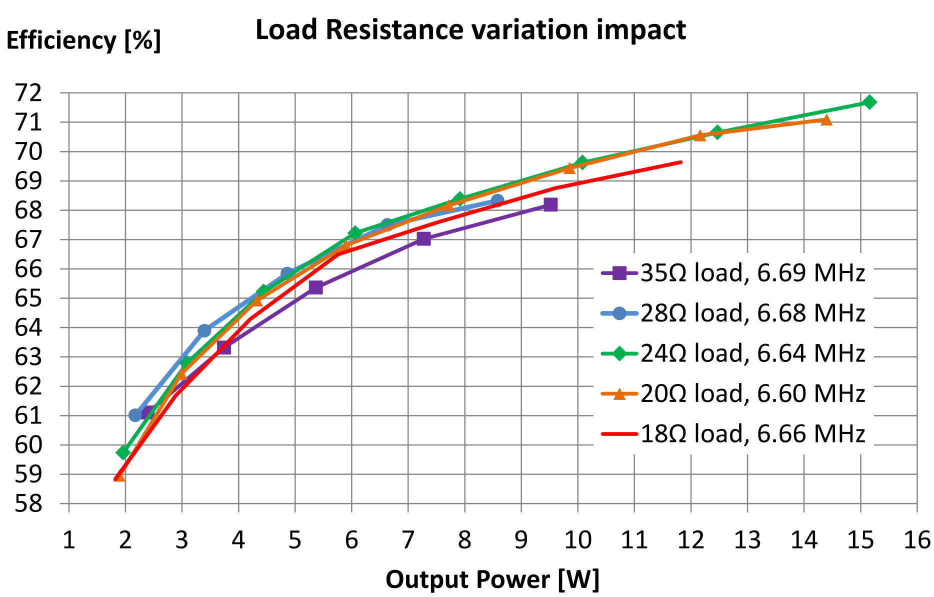

Figure 6. Efficiency of the eGaN FET wireless board as function of output power for various load resistances (excluding gate driver power consumption).

Light loads lead to very high voltages on the source coil winding, and high currents drawn by the source coil and could not be measured to full voltage. A fixed frequency of 6.639 MHz and varying load resistance was also measured and is shown in Figure 7. Due to the nature of the resonances it was not possible to take measurements above 10 V supply as either voltages or currents in the coils became excessive. This result demonstrates the need to be able to operate the system with a fixed load resistance. This can practically be achieved by adding a buck converter whose input behaves as a fixed resistance value.

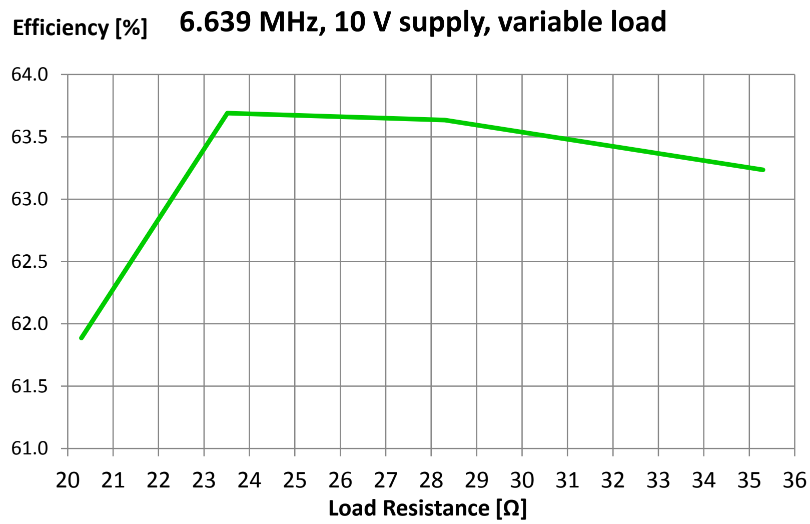

Figure 7. Efficiency of the eGaN FET wireless board as function of load resistance.

It was determined that the peak operating point frequency given a fixed load of 23.6 Ω was 6.639 MHz. Figure 8 shows a graph of load power as function of efficiency including the power consumption of the gate driver circuit for the eGaN FET power amplifier, and having a fixed load resistance of 23.6 Ω while operating at 6.639 MHz.

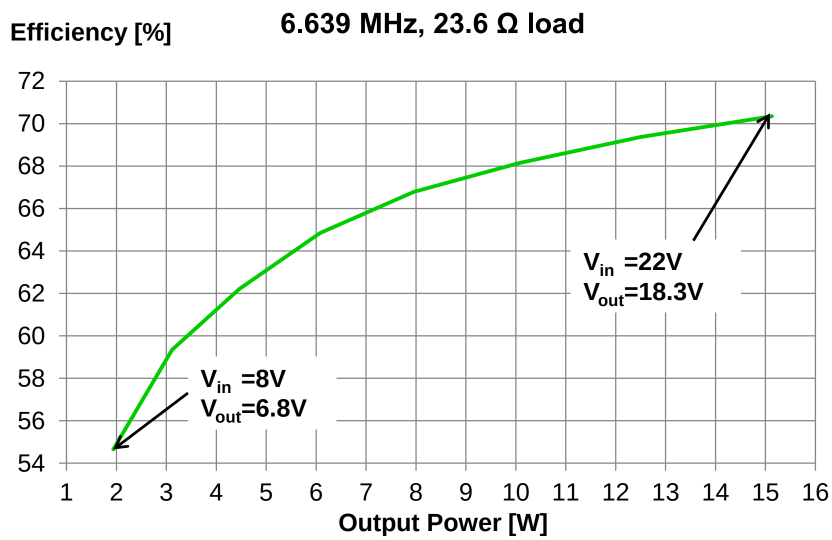

Figure 8. Efficiency of the wireless board as function of output power for a fixed load resistance, DC in to DC out efficiency including gate driver power consumption.

Waveforms were taken at 22 V supply operating are shown in Figure 9. The waveforms shown are lower gate voltage (cyan), switch-node (purple), source coil input current (green) and, device coil output voltage (yellow). The coil current was measured using a Rogowski Coil current probe made by Athena Energy (12). The pick-up sensor was looped around one of the matching inductors on the coil set.

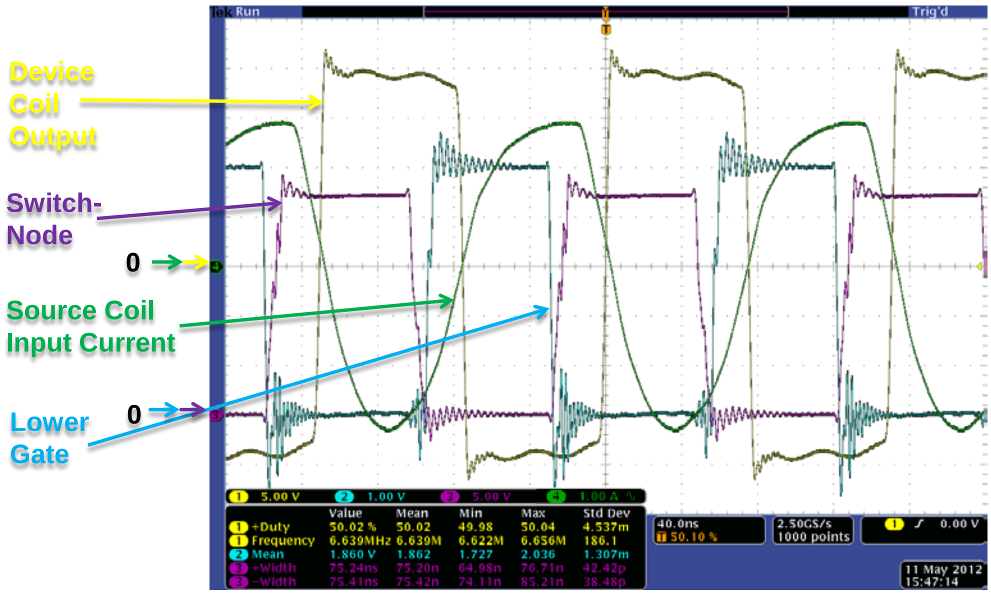

Figure 9. Measurement of eGaN FET board operating at 22 V supply, 6.639 MHz into a 23.6 Ω load.

The system is capable of operating using convection cooling, as shown in Figure 10, up to a supply voltage of 20 V (12.5 W load power). To operate beyond 20 V, forced air cooling was required to keep the one of the matching network inductors from exceeding 150°C.

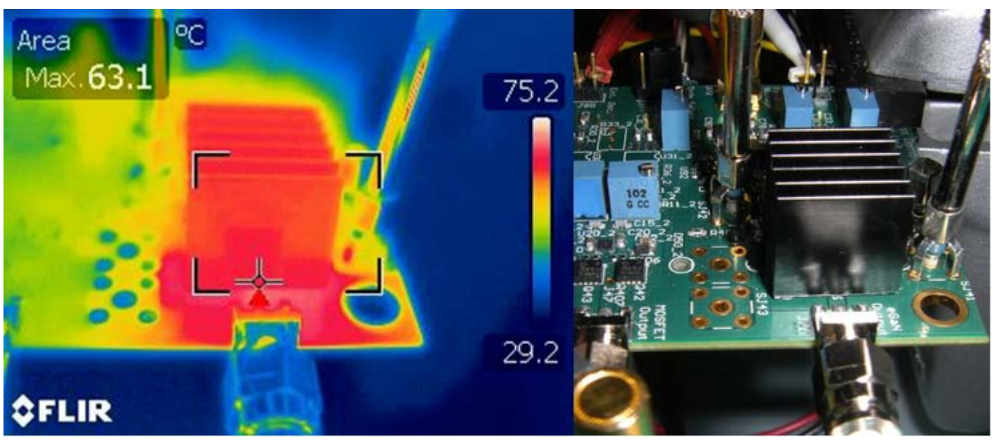

Figure 10. Thermal image of the eGaN FET wireless source board operating at 20 V supply, 6.639 MHz, into 23.6 Ω load (12.5 W) with ambient temperature of 28°C.

A loss breakdown analysis was performed for the eGaN FET wireless board and is shown in Figure 11. Losses were determined for the switching FETs (conduction and switching), gate driver, source board (primary coil), device coil (secondary coil), and rectifier (conduction and capacitive).

Based on the measurements at 22 V supply and load of 15 W the following could be deduced:

1. The induction coil set efficiency is 87.3%
2. The eGaN FET-based system efficiency is 82.9%
3. The MOSFET-based system efficiency is 78.8%
4. The Rectifier efficiency is 93.6%

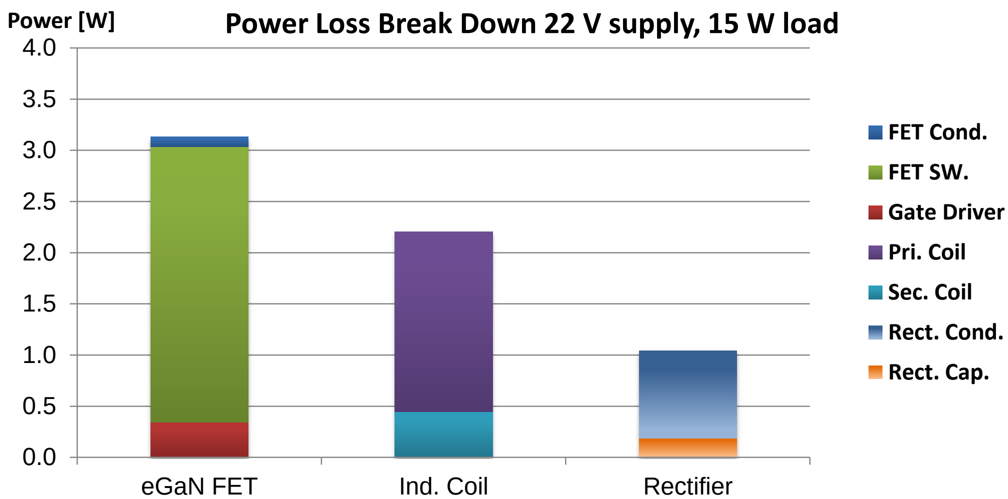

Figure 11. Loss breakdown of the wireless board operating at 22 V supply, 6.639 MHz and load of 23.6 Ω.

Summary

The key to high efficiency operation for a wireless energy system operating in the 6.78 MHz ISM is to load the rectifier with a fixed resistance. This can practically be achieved by loading the rectifier with a buck converter whose input is programmed to operate as a fixed resistor while regulating the output voltage according to load requirements.

Also important to this type of wireless system is to keep the alignment and distance between the coils fixed. The variations in leakage inductance would otherwise become too large to compensate for given the strict bandwidth requirements of operating in the ISM band.

In this article an induction based Class D wireless energy system capable of operating in the ISM band of 6.78 MHz has been demonstrated. Due to experimental constraints, operation was demonstrated at 6.639 MHz.

Finally it should be noted that the eGaN devices used in the evaluation are too large for this application at a 5 W power level. The device chosen was based on the smallest product currently available in the EPC family range. The devices tested enable delivery of 15 W; however, smaller 30 V rated devices could be used for lower power levels with increased efficiency. Alternatively, the supply voltage could be increased to the point where a MOSFET based converter will be unable to operate, resulting in higher power capability for an eGaN FET version.

Acknowledgments

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References

1. Kalyan Siddabattula, *Wireless Power System Design Component And Magnetics Selection*, Texas Instruments presentation on wireless technology, http://e2e.ti.com/support/power_management/wireless_power/m/mediagallery/526153.aspx
2. Witricty Corp. coil set part numbers 190-000037-01 and 190-000038-01, www.witricity.com
3. http://en.wikipedia.org/wiki/Electronic_amplifier
4. John Dooley and Ronan Farrell, *A Practical Class S Power Amplifier for High Frequency Transmitters*, Royal Irish Academy Colloquium on Emerging Trends in Wireless Communications 2008, 23rd & 24th April 2008, Dublin, Ireland.
5. http://en.wikipedia.org/wiki/ISM_band
6. LM5113 datasheet, Texas Instruments, www.ti.com
7. EPC2014 datasheet, www.epc-co.com
8. *System Description, Wireless Power Transfer*, Vol. 1, ver. 1.0.3, Sept. 2011.
9. Johan Strydom, *eGaN® FET- Silicon Power Shoot-Out Volume 8: Envelope Tracking*, Power Electronics Technology, May 2012, http://powerelectronics.com/power_semiconductors/gan_transistors/egan-fet-silicon-power-shoot-out-volume-8-0430/
10. ATS-54150K-C2-R0 datasheet, Advanced Thermal Solutions, www.qats.com
11. Wakefield Engineering thermal interface material P/N 173-7-1212A, http://www.wakefield.com
12. 200A/50MHz Rogowski Coil Current probe, Athena Energy Corp current probe, www.athenaenergycorp.com
13. Teck Chuan Beh, Takehiro Imura, Masaki Kato, Yoichi Hori, *Wireless Power Transfer System via Magnetic Resonant Coupling at Restricted Frequency Range*, Annual Conference of I.E.E. of Japan, Industry Applications Society Aug. 2010.
14. Sam Davis, *Wireless Power Receiver IC Complements Existing Transmitter*, Power Electronics Technology magazine, July 2011.
15. Shahrzad Jalali Mazlouman, Alireza Mahanfar, Bozena Kaminska, *Mid-range Wireless Energy Transfer Using Inductive Resonance for Wireless Sensors*, IEEE International Conference on Computer Design ICCD 4-7 Oct 2009. pp 517 – 522.
16. *Wireless Power Transfer Enabling the Mobile Charging Ecosystem*, by Qualcomm, Presented at the Darnell Power Forum, Sept. 2011.