Abstract — In this work, we propose the design and implementation of a 13.56 MHz GaN Class-E power amplifier, which takes into account transistor parasitic effects. The design uses the parasitic capacitance of the transistor to replace the charging capacitance, simplifying the circuit structure and obtaining a 93.6% efficiency at output power of 26.8 W. In addition, a wireless power transfer system using the proposed Class-E amplifier is demonstrated, achieving a 73.4% system efficiency when the power delivered to the load is 25.6 W.

Index Terms — Power transmission, energy efficiency, power MOSFET, silicon carbide, gallium nitride, power amplifiers.

I. INTRODUCTION

Wireless power transmission (WPT) technology has been gaining strong attention among researchers because not only is it used to charge consumer products, it also contributes to other technical fields, for instance, supplying the power to sensors embedded in a human body or charging a moving vehicle on the highway. Major blocks in a WPT system include the power amplifier, the transmitting and receiving coils, and the receiver. Within the system, the power amplifier is the most important component because it determines the performance of the system, acting not only as the power converter, but also as the control mechanism. Therefore, this paper proposes a high efficiency GaN power amplifier for the WPT application to obtain an excellent characteristic.

Generally, switching power amplifiers, such as Class-D or Class-E are the candidates of the WPT systems because of their high efficiency, approaching 100% theoretically. Compared to other types of switching power amplifiers, the Class-E has fewer components, yielding high reliability. However, according to Sokal [1], the entire capacitance, including shunt capacitor and C_{ds}, between drain and ground limits the operating frequency of the transistor in the Class-E power amplifier. High C_{ds} prevents Class-E from realizing zero voltage switching (ZVS) and reaching 100% efficiency at high frequency. Therefore, in this design, C_{ds} is used without an additional shunt capacitor from the drain to ground, simplifying the circuit structure while keeping the same performance.

Several methods have been proposed to achieve wireless power transmission, such as magnetic coupling, electromagnetic coupling, magnetic resonance, and microwave power transmission. Among these technologies, electromagnetic coupling can realize highest efficiency between 70% and 90% [2]. In past years, several magnetic coupling WPT systems also have been demonstrated [3-5]. However, the components used in these systems are large because those operating frequencies are below 500 kHz. One way to achieve a miniature and light-weight WPT system is increasing the operating frequency, such as 13.56 MHz, which is RFID operating frequency and will allow users to transmit high power. As the operating frequency is increased, the coupling effect between the two coils becomes stronger [6]; thus, using the smaller coils can obtain the similar performance at the lower frequency. Unfortunately, compared to designing a WPT system below 500 kHz, it is more difficult to realize a WPT system at 13.56 MHz because the parasitic effects become significantly larger.

Regarding the transistor used in designing a power amplifier, the high-voltage silicon power MOSFET has been a popular choice for low frequency applications, but the switching frequency is limited by the large device capacitance due to the chip area and packaging structure. On the other hand, unlike the silicon power MOSFET, SiC (silicon carbide) and GaN (gallium nitride), which are wide-bandgap materials, are excellent at the on-resistance and gate-charging. Moreover, they have very low parasitic capacitance such as C_{gs} and C_{ds}, which means the transistor enables circuits to operate at a higher switching frequency. These two types of transistors were evaluated by using CMF20120D, a SiC power MOSFET and EPC1010, a GaN enhancement mode power transistor, both achieving a drain voltage rating of 200 V. The EPC1010 GaN transistor has a lower C_{gs} capacitance and on-resistance because of a small size (3.5 mm × 1.4 mm) and wafer-level package. Therefore, it can have a higher efficiency and lower gate-driving power. As a result, the EPC1010 GaN transistor was selected for the Class-E power amplifier in this work.

A 26.8 W 13.56 MHz GaN power amplifier with a 93.6% efficiency was designed and measured. This result is described in section II. The discussion of the experiment and gate biasing voltage condition are also presented. Section III demonstrates the WPT system consisting of the proposed Class-E power amplifier, coupling coils, and rectifier circuit. The WPT system delivers 25.6 W to the receiver load with a system efficiency of 73.4%.

II. HIGH EFFICIENCY 13.56 MHz CLASS-E POWER AMPLIFIER

Fig. 1 shows the schematic of a traditional Class-E power amplifier composed of a transistor, an RF choke L1, a shunt capacitance C1, a resonator circuit including C2 and L2, and a...
load resistor R. Those component values can be calculated by the equations listed in [1]. In the design, $C_{ds}$ of the GaN transistor is used to replace $C_1$, simplifying the circuit structure while keeping the same performance. The component values are $L_1 = 50 \, \mu \text{H}$, $C_2 = 690 \, \text{pF}$, $L_2 = 0.3 \, \mu \text{H}$, and $R = 13 \, \Omega$. For the gate-driving circuit design, a K50-HC oscillator is used to generate a 13.56 MHz clock, which is then amplified by an IXD1502 gate driver to drive the GaN transistor.

![Fig. 1. Schematic diagram of the Class-E Power Amplifier.](image1)

The waveforms and power delivered to load resistor R were measured by using a current probe (Tektronix X004062), voltage probes (Tektronix P2220), and an oscilloscope (Tektronix TDS2004B). Fig. 2 displays the voltage waveforms at the drain and input clock signal at the gate when the supply voltage $VDD$ is 25 V. The output current and voltage waveform at load resistor R are shown in Fig. 3. If R is an ideal resistor, the current and voltage waveform should be in-phase. However, at 13.56 MHz, this resistor has parasitic capacitance and inductance, causing 11 degrees phase difference between the two waveforms.

Fig. 4 demonstrates the drain voltage versus the efficiency and output power. Because the power consumption of the gate-driving circuit is 370 mW, the efficiency of the circuit at low output power is relatively small. If the $C_{gs}$ of the transistor is larger, the gate-driving circuit consumes more current to drive the transistor. Therefore, choosing a transistor with a low $C_{gs}$ is very important, especially when the output power is not high. In this design, without considering the power consumption of the gate-driving circuit, the highest output power at the load is 26.8 W with a drain efficiency of 93.6% when $VDD$ is 27 V and the gate-driving circuit supply voltage is 5 V. Fig. 4 also indicates that the GaN transistor is more efficient when generating high power. For instance, the drain efficiency increases 5.4% when the output power is from 9.8 W@VDD = 17 V to 26.8 W@VDD = 27 V. Because a heat sink was not added to the circuit, 27 V is the highest testing voltage in this study. The relation among the gate-driving circuit supply voltage, the output power, and efficiency is displayed in Fig. 5. The gate-driving circuit supply voltage range is from 4 to 6 V, while the VDD is set to 25 V. This graph shows the circuit can perform more efficiently when it is supplied by a high gate-driving voltage. However, 6 V is the limitation at the input of the GaN transistor, and therefore 5 V is used to prevent possible damage.

![Fig. 2. Drain and gate waveforms.](image2)

![Fig. 3. Voltage and current waveforms at load resistor R.](image3)

![Fig. 4. Output power (solid squares), drain efficiency (hollow circles), and total efficiency (hollow triangles) versus drain supply voltage. Total efficiency calculation includes power consumption in the gate-driving circuit.](image4)

Table 1 lists the results of two previously published similar works as well as this work that shows higher output power with a higher drain efficiency.

### III. DEMONSTRATION OF 13.56 MHZ WPT SYSTEM

Fig 6 illustrates the schematic diagram of the WPT system, including the proposed Class-E power amplifier, coupling...
coils, rectifier circuit, and matching networks. The coils, consisting of two concentric coils of the same length, designed by magnetic coupling method, were utilized to transfer a 13.56 MHz signal generated from the Class-E power amplifier. The mutual inductance between the coils is 0.49 µH when L3 is 0.92 µH with a parasitic resistance of 4.8 Ω; and L4 is 0.56 µH with a parasitic resistance of 2.6 Ω, measured at 13 MHz. After the 13.56 MHz signal couples from L3 to L4, the full-bridge rectifier, composed of four SK310A diodes and a capacitor C5 of 68 µF, rectifies the AC signal to DC power. [4] explains the four topologies for a single-element impedance transformation network, and the series-series topology, realized by C3 of 132 pF and C4 of 150 pF, was selected for the WPT system to achieve the maximum power transmission. Fig. 8 demonstrates the characteristic of the WPT system with different load resistances. When Rload is 350 Ω, the system achieves 73.4% efficiency when the power delivered to Rload is 25.6 W.

**IV. CONCLUSION**

The proposed Class-E power amplifier achieves 26.8 W output power with an efficiency of 93.6% at 13.56 MHz. A WPT system using this amplifier achieves power delivery of 25.6 W with a 73.4% system efficiency. This demonstrates that the GaN transistor is a suitable choice for a WPT system at this frequency.

**REFERENCES**


