A Compact Class E Rectifier for Megahertz Wireless Power Transfer

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***Abstract*—It is promising for consumer electronics to achieve the long wireless charging distance by increasing the system frequency to megahertz. For MHz systems, hard-switching-based rectifiers(e.g., the full-bridge rectifier) will have significant switching loss. Therefore, it is attractive to apply the soft-switching techniques for MHz rectifiers. The Class E rectifier is a proper candidate for MHz system due to its soft-switching topology. This paper presents a compact Class E rectifier for megahertz wireless power transfer. The equivalent circuit model and simulation are presented to analyze behavior of the proposed rectifier. Finally, a 6.78 MHz Class E rectifier is implemented and experiment results show that proposed system can achieve a 92% efficiency with an input power of 10 W.**

***Index Terms*—Wireless power transfer, Class E rectifier, resonant inductive coupling**

I. Introduction

In recent years, the wireless power transfer (WPT) based on resonant inductive coupling becomes more and more attractive due to its unique advantage, namely the wireless charging for various electronic devices. For most of consumer electronics, it is promising to increase the system frequency to several MHz for larger spatial freedom, which can even enable the charging of multiple devices simultaneously [1]. In order to build a well-performed MHz WPT system, most of researches focus on the design and optimization for those important subsystems, including the resonant coupling system [1], [2], the power amplifier [3], and the dc/dc converter for load control [4], [5]. However, there has been few works on high-efficiency rectifiers for MHz WPT applications. Usually, most WPT systems use the hard-switching-based rectifiers, for example the full-bridge rectifiers. However, these hard-switching topologies will have significant switching loss when working at MHz. Therefore, it is desirable to apply the soft-switching techniques for MHz rectifiers. The Class E rectifier is one of most promising candidates for high-frequency rectification due to its resonant structure. The well-designed resonant structure enable the zero-voltage switching (ZVS) or the zero-current switching (ZCS) and can reduce the swiching loss. Therefore, it is attractive to introduce the Class E rectifier for MHz wireless power transfer.

The Class E rectifier was first presented and used for very high frequency dcdc converter in [6] at 1988. Then various Class E topologies have been developed, such as half-wave, full-wave, and mixed-mode rectifiers [7]. However, there are few works discussing the use of Class E rectifiers for WPT systems. The use of Class E rectifier in resonant wireless power transfer system is first investigated in [8] at 800 kHz operating frequency. In this paper, a piecewise linear state-space representation is used to model the Class E rectifier and calculate the parameters for the optimal operation. In [9], a 200 kHz WPT system is build with a Class E^2 topology, i.e., a Class E power amplifier and a Class E rectifier. However, those systems are still working at frequencies below 1 MHz. Based on the system structure of [8], a 5.56 MHz WPT is introduced in [10] by merely adding the resonant Class E rectifier after the receiving coil. Such a system configuration will use large series inductor to form resonant circuit for the Class E rectifier. The bulky resonant inductor is not suitable to be introduced for the common consumer electronics, which have strict requirement on the component size. Therefore, it is desirable to develop small and compact Class E rectifiers for real applications. According the well-developed research for Class E rectifiers, a suitable Class E topology is chose and the required resonant inductor is absorbed into the self-inductance of the receiving coil. Thus the use of the large inductor can be avoided and a system with small size is possible.

This paper is organized as follows. It first reviews the Class E rectifier in WPT systems, and gives the circuit configuration of the proposed compact Class E rectifier. The leak inductance of the receiving coil is designed as the resonant inductor for the Class E rectifier. Then a circuit-model-based analysis is carried out to evaluate the characteristics of the rectifier. It gives the system analysis under different coupling coefficient and load. After the analysis for the Class E rectifier, the coupling coils are added to provide a overall system analysis. Finally, a experiment is carried out to verify the circuit analysis.

II. System Analysis

A. Traditional Class E Rectifiers

Fig. 1 shows the typical circuit models of voltage driven [11] and current driven Class E rectifier [12], respectively. In those circuit models, the diode parasitic capacitor can be absorbed by the parallel capacitor C, which is designed to be resonant with the inductor L. C_o is a filter capacitor and R is the load. The LC series resonant circuit enables the ZVS or ZCS for the Class E rectifier. These benefits are attractive for high-frequency rectification, especially when the system frequency is above MHz.

The Class E rectifier is first introduced for high-frequency rectification in a 800 kHz system [8]. Their system [refer to Fig. 2] consists of a power amplifier, two coupling coils, and a

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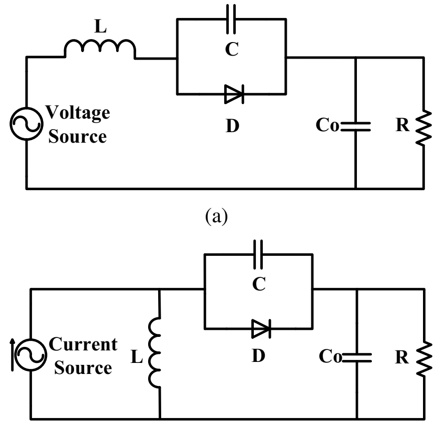


(a)

(b)

Fig. 1. Typical circuit model. (a) Voltage driven Class E rectifier. (b) Current driven Class E rectifier.

Class E rectifier. In this topology, the parallelled compensated receiving coil is viewed as a voltage source to drive the rectifier in Fig. 2(a). However, a large resonant inductor 39.5 μH is required to tune the resonance for their rectifier. This inductor is usually bulky and cannot be directly used in the compact wireless charging system, such as mobile phones and laptops.

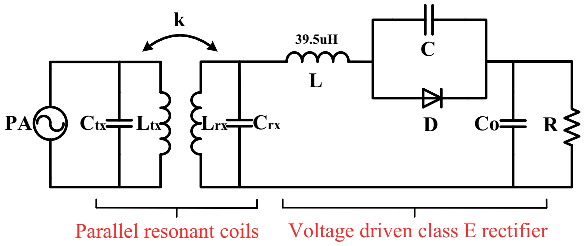


Fig. 2. System configuration in [8].

B. The Compact Class E Rectifier

Fig. 3 shows the proposed compact Class E rectifier, which is driven by the coupling coils. In this structure, L_{tx} and R_{tx} are the self-inductance and parasitic resistance of the transmitting coil. The transmitting coil is tuned to resonance by

$$j\omega L_{tx} + \frac{1}{j\omega C_{tx}} = 0, \tag{1}$$

where ω is the resonant frequency. L_{rx} and R_{rx} are the self-inductance and parasitic resistance of the receiving coil. Different to the structure in Fig. 2, a diode D with shunt capacitor C is added directly after the receiving coil to form a resonant Class E rectifier.

In order to explain the working mechanism for the proposed topology, the equivalent circuit model is given in Fig. 4 (a). In this model, the receiving coil L_{rx} can be viewed as two parts, the mutual inductance L_m and the leak inductance $L_{tx} - L_m$. The mutual inductance L_m can be represented as,

$$L_m = k\sqrt{L_{tx}L_{rx}} \tag{2}$$

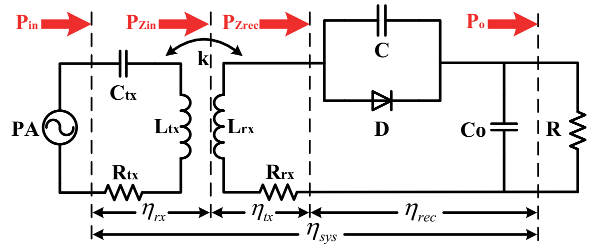
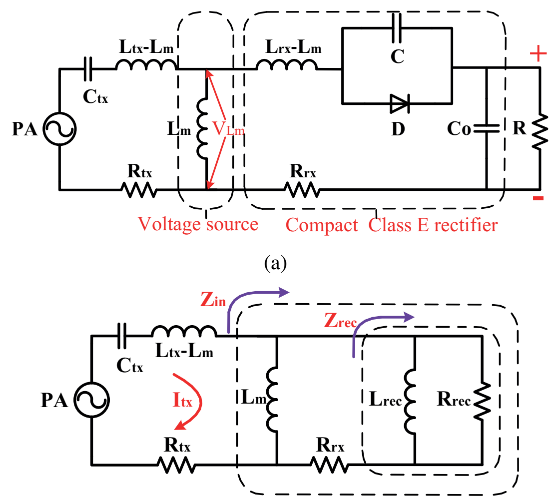


Fig. 3. The proposed compact Class E rectifier.

where k is the mutual-inductance coefficient. The leak inductor is used to form the resonant Class E rectifier by

$$j\omega(L_{tx} - L_m) + \frac{1}{j\omega C} = 0. \tag{3}$$



(a)

(b)

Fig. 4. Equivalent circuit model. (a) The proposed rectifier. (b) The circuit model based on [11].

According to Fig. 1 (a), this topology requires a sinusoidal voltage resource to drive the rectifier. It is first assumed that V_{Lm} is a sine voltage. Then according to [11], the circuit of Fig. 4 (a) can be further simplified with a circuit as shown in Fig. 4 (b). The rectifier can be represented by a parallel connected resistance R_{rec} and inductor L_{rec}. Using this model, the KVL function can be applied to show that the voltage of L_m is a sine wave. Because

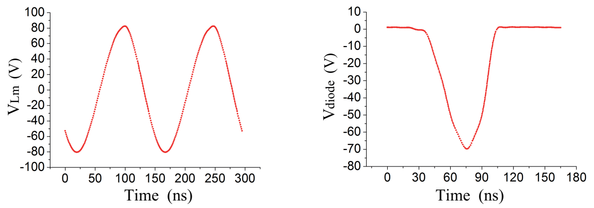
$$V_{Lm} = I_{tx}Z_{in}, \tag{4}$$

where I_{tx} is the current of transmitting coil. Finally, it can be found that the assumption for sine V_{Lm} is valid.

Usually, a Class E rectifier is designed to have a 50% duty cycle for the diode to achieve optimum operation. This duty cycle depends on the parameters of rectifier, such as L and R. The behavior of such a standard Class E rectifier has been described in [11]. According to this paper, a 6.78 MHz rectifier is built and it can achieve the optimum operation when R is 32 Ω at $k = 0.3$. Using this load, a simulation is carried out in a widely used RF software Advanced Design System (ADS). The Pspice model of diode $STPSC406$ is used. The simulation parameters are given in Table I. Fig. 5 gives the voltage waveforms for L_m (V_{Lm}) and diode (V_{diode}). It shows that the V_{Lm} is a sine voltage and the duty cycle of diode is 50%.

TABLE I
PARAMETERS IN SIMULATION

L_{tx}	C_{tx}	R_{tx}	L_{rx}	R_{rx}	C
2.705 μH	203 pF	0.5 Ω	2.71 μH	0.7 Ω	290 pF



(a) (b)

Fig. 5. Simulation results. (a) The voltage cross L_m. (b) The voltage cross diode.

According to the traditional analysis, a Class E rectifier is properly designed to give a optimal output under fixed parameters given in [11]. However, the parameters of the Class E rectifier cannot be fixed in a WPT system. Because there are two unavoidable uncertainties, i.e., the variation of the coil's position and the load. It means that k and R can be changed in application. In order to evaluate the rectifier under these uncertainties, the following gives the system performance for different k and R.

When the coupling changes, the resonant frequency between (L_{rx}-L_m) and C is no longer 6.78 MHz, and the exact resonant frequency for different k are recorded in Table II. As shown in Fig. 3, the efficiency of the rectifier can be derive as

$$\eta_{rec} = \frac{P_o}{P_{Zrec}}, \tag{5}$$

where P_o is the output power of the rectifier and P_{Zrec} is the output power of the receiving coil. Using simulation, Fig. 6 gives the efficiency for a different k when R = 32 Ω and the input power is 10 W. It shows that the efficiency is high and stable for a varying k. The peak efficiency occurs when $k = 0.3$ because of the resonance. In conclusion, the variation of k has limited effect on the rectifier efficiency. For the different R, the efficiency is given in Fig. 7. It shows that the rectifier can realize a high efficiency for a wide load range.

TABLE II
THE RESONANCE FREQUENCY IN DIFFERENT K

k	L_m	L_{rx}-L_m	Resonant FREQ
0.10	0.2708 μH	2.4367 μH	5.99 MHz
0.15	0.4061 μH	2.3014 μH	6.16 MHz
0.20	0.5415 μH	2.1660 μH	6.35 MHz
0.25	0.6769 μH	2.0306 μH	6.56 MHz
0.30	0.8123 μH	1.8952 μH	6.78 MHz
0.35	0.9478 μH	1.7622 μH	7.04 MHz
0.40	1.0832 μH	1.6268 μH	7.33 MHz
0.45	1.2186 μH	1.4914 μH	7.65 MHz
0.50	1.3540 μH	1.3560 μH	8.03 MHz

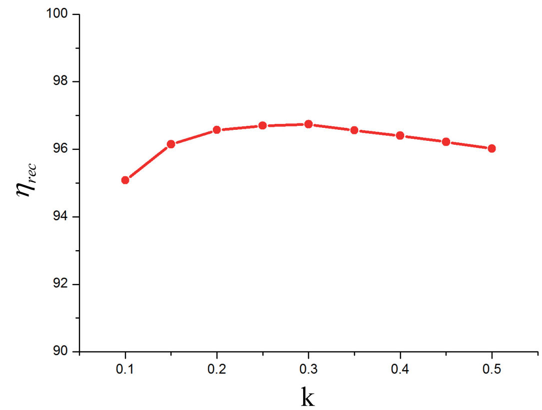


Fig. 6. The rectifier efficiency for different k when R = 32 Ω.

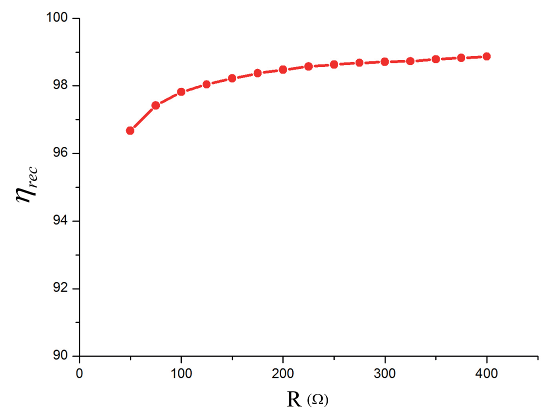


Fig. 7. The rectifier efficiency for different R when k = 0.3.

C. The WPT System Using the Compact Class E Rectifier

The compact Class E rectifier can achieve a high efficiency for different k and load R. However, in a WPT system, the high efficiency of the rectifier cannot ensure a high overall system efficiency. Therefore, it is necessary to evaluate the system efficiency when considering both the coupling coils and the rectifier. According to the circuit model shown in Fig. 3, the system efficiency η_{sys} can be obtained by the product of the transmuting coil efficiency η_{tx} and the receiving coil efficiency η_{rx}. In this system, the impedances Z_{rec} and Z_{in} can be used to calculate the efficiency η_{tx} and η_{rx}. Based on the circuit model in Fig. 4(b), the impedance Z_{rec} can be derived as:

$$Z_{rec} = \frac{R_{rec}\omega^2 L_{rec}^2}{R_{rec}^2 + \omega^2 L_{rec}^2} + j\frac{R_{rec}^2 \omega L_{rec}}{R_{rec}^2 + \omega^2 L_{rec}^2}. \tag{6}$$

The efficiency of the receiving coil is

$$\eta_{rx} = \frac{Real\left[Z_{rec}\right]}{Real\left[Z_{rec}\right] + R_{rx}}, \tag{7}$$

where Real[*] means taking the real part. According to Fig. 4(b), the impedance Z_{in} can be derived as:

$$Z_{in} = \frac{R_{rec}\omega^2 L_{in}^2}{R_{rec}^2 + \omega^2 L_{in}^2} + j\frac{R_{rec}^2 \omega L_{in}}{R_{rec}^2 + \omega^2 L_{in}^2}, \tag{8}$$

where

$$L_{in} = \frac{L_{rec} L_m}{L_{rec} + L_m}. \tag{9}$$

Similarly, the efficiency of transmitting coil is

$$\eta_{tx} = \frac{Real\left[Z_{in}\right]}{Real\left[Z_{in}\right] + R_{tx}}, \tag{10}$$

Therefore, the system efficiency can be calculated as

$$\eta = \eta_{tx} * \eta_{rx}. \tag{11}$$

According to [11], the value of R_{rec} and L_{rec} can be calculated for different load R. Substituting these value into (6) and (8), the impedance Z_{rec} and Z_{in} can be obtained. Then, the system efficiency can be calculated by using (7), (10) and (11). Fig. 8 gives the system efficiency of calculation and simulation for a variable load R. It shows that the efficiency increases with R increases and stop increasing when $R \geq 300\ \Omega$ for simulation and calculation. The simulation efficiency is higher than the calculation results due to the calculation error of R_{rec} and L_{rec} given in [11].

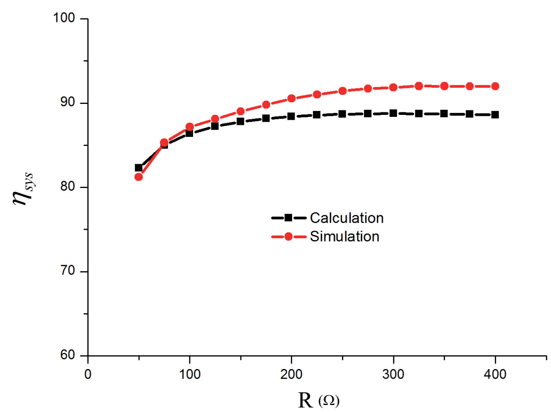


Fig. 8. The system efficiency of calculation and simulation for different R.

III. Experiment

A 6.78 MHz WPT system with both the coupling coils and the Class E rectifier is implemented to verify the system analysis. The experiment setup is shown in Fig. 9. It includes a power amplifier, two coupling coils, a Class E rectifier and an electrical load. STPSC406 is used as the rectifying diode and the parasitic capacitance of this diode is about 30 pF. The distance of coils is 20 mm ($k = 0.3$). Under this distance, the resonant capacitor C is chose to be 290 pF according to (2) and (3) when considering the diode parasitic capacitance.

In this experiment, the rectifier efficiency cannot be directly obtained because its resonance inductor (L_{rx}-L_m) is a part of the receiving coil. Therefore, the experiment gives the system efficiency instead of the rectifier efficiency. The input power of this system can be adjusted by the power amplifier. The system efficiency for the different load is evaluated with an input power of 10 W. The result is given in Fig. 10. It shows that the system efficiency is high for a wide load as the simulation predicts. The waveforms of diode voltage and diode current are given in Fig. 11. It shows that the duty cycle of diode is 50% when $R = 32\Omega$ and $C = 290pF$, which is in accordance with the circuit analysis for the compact rectifier. The oscillation observed in diode current is due to the lead inductances of the diode and the current probe.

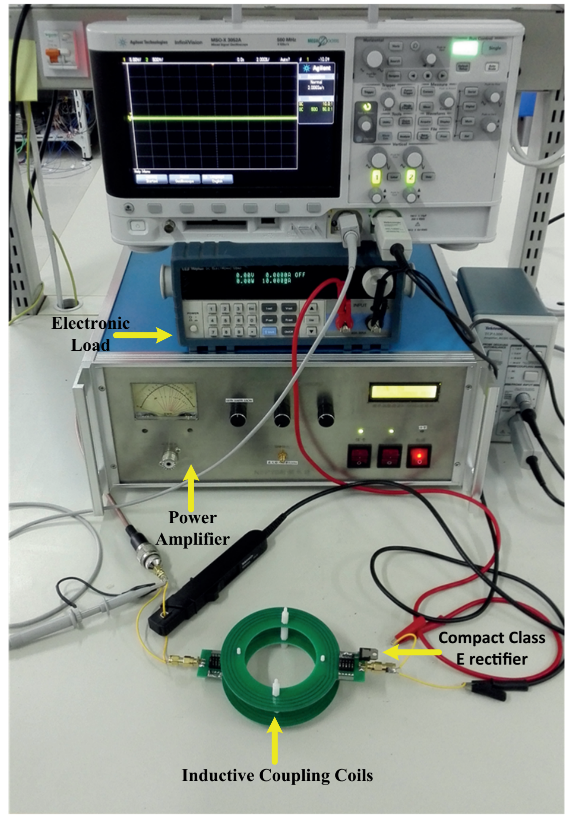


Fig. 9. The experiment setup.

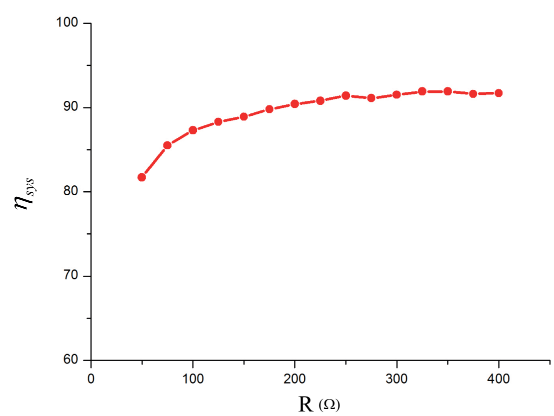


Fig. 10. The system efficiency for different R.

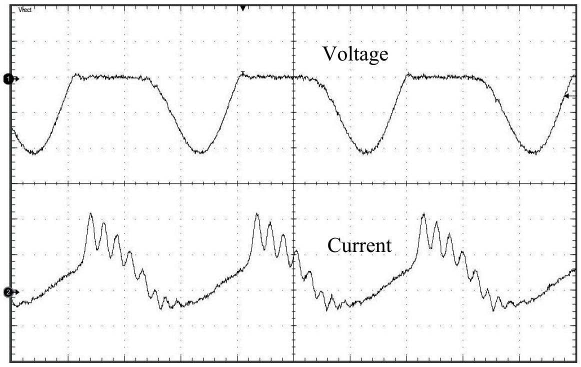


Fig. 11. The system efficiency for different P_{in}.

IV. Conclusions

This paper presents a compact Class E rectifier for the MHz wireless power transfer system. The typical Class E rectifiers are reviewed to discuss their potential advantages for WPT application. The leak inductance of the receiving coil is used as the resonant inductor of the Class E rectifier. The traditional analysis for the rectifier is used to analyze behavior of the proposed structure. Through simulation, it shows that the Class E rectifier can achieve high efficiency for a wide range of coupling coefficient and load. Besides, the coupling coils are also added into system analysis together with the proposed rectifier. In the final experiment, a high overall system efficiency 92% is observed at 10 W, which successfully verify the system analysis.

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