

# Low-Harmonic-Contents and High-Efficiency Class E Full-Wave Current-Driven Rectifier for Megahertz Wireless Power Transfer Systems

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**Abstract**—Wireless power transfer (WPT) working at megahertz (MHz) is now being widely considered a promising candidate for the mid-range transfer of a medium amount of power. Efforts have been made to build high-efficiency MHz WPT systems via both component- and system-level approaches. However, so far there have been few discussions on high frequency rectifier for MHz WPT applications. The soft-switching-based rectifiers, such as the Class E rectifiers, are one of promising candidates for MHz rectification. This paper investigates the application of a Class E full-wave current-driven rectifier, for the first time, in WPT systems. A procedure is also developed to optimize the design of the rectifier and the MHz WPT system. For comparison purposes, the performances of both the Class E rectifier and the conventional full-bridge rectifier are investigated in terms of total harmonic distortion (THD), efficiency, power factor, voltage/current stresses, and voltage/current transfer functions, when being applied in an example 6.78 MHz WPT system. The simulation and experimental results show that the input voltage THD of the Class E full-wave rectifier is reduced to one fourth of the THD of the full-bridge rectifier. In the optimally designed MHz WPT system, efficiencies of both the rectification (over 91%) and the overall system (around 80%) are obviously improved compared to the system using the conventional full-bridge rectifier.

**Index Terms**—Megahertz Wireless power transfer, Class E full-wave current-driven rectifier, Low-harmonic contents, Efficiency

## I. INTRODUCTION

There is now a dramatic need in charging various electronic devices (e.g., cellphones, laptop computers, wearable devices, medical implant devices, etc.) and other high-power systems, especially electric vehicles. This need makes the wireless power transfer (WPT) using inductive resonance coupling, i.e., the so-called inductive coupling and magnetic resonance coupling, increasingly popular in recent years [1], [2]. Currently WPT working at kilohertz (kHz) is making significant progress in power level, system design, and applications [3]–[7]. Meanwhile, for medium- and low-power applications, further increasing the resonance frequency such as to several megahertz (MHz) brings a higher level of spatial freedom, namely a longer transfer distance and higher tolerance to

coupling coil misalignment, and is desirable for building more compact and lighter WPT systems [2], [8]. Now WPT working at megahertz (MHz) is being widely considered a promising candidate for the mid-range transfer of a medium amount of power. Meanwhile, in MHz WPT systems ultra high speed logic gates are required to drive the MOSFET switches. This leads to increased gate power dissipation and cost. The soft-switching operation of the power amplifier (PA) and the rectifier is also expected to reduce the increased switching losses [9], [10]. Besides, generally the parasitic resistances of the ac inductors including the coupling coils increase at MHz. It is especially desirable to use high-Q (quality factor) inductors and coupling coils for conduction loss reduction [11]. Moreover, the impedance characteristics of circuits working at MHz are much more complicated than those at kHz. For instance, at MHz the influence of the parasitic and/or parallel capacitors of the diodes becomes significant. This causes non-neglectable reactance of the rectifier that could lower the efficiency and power transfer capability of the system [12]. In addition, electromagnetic interference (EMI) problem in the MHz WPT systems is also more challenging. In order to improve the overall performance of the MHz WPT systems, it is important to introduce new topologies of the circuits, and conduct comprehensive analysis and optimization.

Efforts have been made to build high-efficiency MHz WPT systems via both component- and system-level approaches focusing on the improvements in coupling coils [13]–[17], PA [18]–[21], and load control [22]–[24]. At the same time, so far there have been few discussions on high frequency rectifier for MHz WPT applications. Most existing MHz WPT systems use conventional hard-switching-based rectifiers such as the full-bridge rectifier. Due to the hard-switching operation, there is significant switching loss from the full-bridge rectifier when operating at MHz. In addition, the hard switching also leads to high voltage harmonic contents in WPT systems due to the square-wave input voltage in the full-bridge rectifier. For a high frequency rectification at MHz, the soft-switching-based rectifiers, such as the Class E rectifiers, are one of promising candidates. Meanwhile, care should be taken to use proper diodes due to the higher diode voltage stress in the Class E rectifiers [25]. The Class E rectifier was first proposed for a high-frequency dc-dc converter in 1988 [26]. Various Class E topologies were later reported including voltage/current-driven and half-wave/full-wave ones [27]–[32].

The research on high-frequency rectification in WPT system is relatively new. Among the following few existing references,

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[33] discussed, for the first time, the application of the Class E rectifier in a 800 KHz WPT system. In [33] a piecewise linear state-space representation is used to model and design the Class E rectifier. A 200 KHz Class  $E^2$  WPT system was later built, i.e., a combination of a Class E PA and a Class E rectifier [34]. Initial discussions on applying the Class E rectifier in MHz WPT systems can be found in [35], [36], where the real implementation and the simulation-based analysis of the Class E rectifiers were introduced, respectively. [25] reported new progress on the system-level optimization of a 6.78 MHz WPT using the Class E rectifier. In the above references all the Class E rectifiers are half-wave, and thus their input current or voltage waveforms are nonsinusoidal and asymmetric. This disadvantage causes high harmonic contents in the input voltage/current of the rectifiers, and thus adversely influences the efficiency and EMI performance of the MHz WPT systems. It is known that the input voltage/current harmonic contents of the rectifier can disrupt the resonant operation of the coupling coils and the Class E PA [33]. And poor EMI performance may affect other nearby electronic devices and eventually limit the usage of the WPT system. Thus it is important to investigate and develop a low-harmonic-contents and high-efficiency rectifier that targets the applications in MHz WPT.

This paper investigates the application of a Class E full-wave current-driven rectifier, for the first time, in MHz WPT systems, particularly the optimized design of the overall WPT system when using the rectifier. Because of the sinusoidal input voltage and current, this soft-switching-based rectifier is a promising candidate for low-harmonic-contents and high-efficiency rectification at MHz. Based on the newly derived input impedance of the Class E full-wave rectifier, the parameters of the coupling coils and the PA are further optimized for a high efficiency of the overall WPT system. For comparison purposes, the performances of both the Class E rectifier and the conventional full-bridge rectifier are investigated in terms of total harmonic distortion (THD), efficiency, power factor, voltage/current stresses, and voltage/current transfer functions, when being applied in an example 6.78 MHz WPT system. The simulation and experimental results show that the input voltage THD of the Class E full-wave rectifier is reduced to one fourth of the THD of the full-bridge rectifier. In the optimally designed MHz WPT system, efficiencies of both the rectification (over 91%) and the overall system (around 80%) are obviously improved compared to the system using the conventional full-bridge rectifier.

## II. CLASS E FULL-WAVE RECTIFIER

The circuit model of the Class E full-wave current-driven rectifier is shown in Fig. 1. The current-driven topology is chosen because it can be applied both in parallel-series and series-series WPT systems. The rectifier consists of two filter inductors,  $L_1$  and  $L_2$ , two parallel capacitors,  $C_1$  and  $C_2$  with an identical capacitance  $C$ , two rectifying diodes,  $D_1$  and  $D_2$ , a filter capacitor  $C_o$ , and a dc load,  $R_L$ .  $P_{rec}$  and  $P_o$  are the input/output power of the rectifier, respectively. In this paper two silicon carbide diodes, STPSC406, are used as the

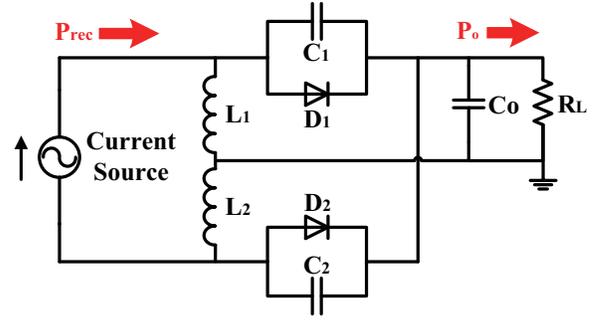


Fig. 1. Circuit model of the Class E full-wave current-driven rectifier.

rectifying elements, and their parasitic capacitors are absorbed by the parallel capacitors. Fig. 2 shows four operating modes of the full-wave rectifier during one switching period. In the figure the input current of the rectifier,  $i_{rec}$ , is sinusoidal;  $i_{D_1}$  and  $i_{D_2}$  are the currents through diode  $D_1$  and  $D_2$ ;  $i_{C_1}$  and  $i_{C_2}$  are the currents through  $C_1$  and  $C_2$ ;  $I_o$  is the dc output current of the rectifier. Since the inductances of  $L_1$  and  $L_2$  are equal and sufficiently large, the currents through the two inductors are equal to  $I_o/2$ . In the rectifier  $i_{C_1}$  and  $i_{C_2}$  shape the waveforms of the voltages across  $D_1$  and  $D_2$ , and thus turn on and off the two diodes. For example, as shown in Fig. 2(a),  $D_1$  is turned on and  $D_2$  is turned off. The currents,  $I_o/2+i_{rec}$  and  $I_o/2-i_{rec}$ , flow through  $D_1$  and  $C_2$ , respectively. Because the current through the parallel combination of  $C_o$  and  $R_L$  is  $(I_o/2+i_{rec}) + (I_o/2-i_{rec})$ , theoretically the output current of the rectifier is a pure dc. In real applications the circuit can not be completely symmetrical. The filter capacitor  $C_o$  is still needed, but its capacitance is much smaller than that in conventional rectifiers such as the full-bridge rectifier. The operations in the other three modes can be similarly explained.

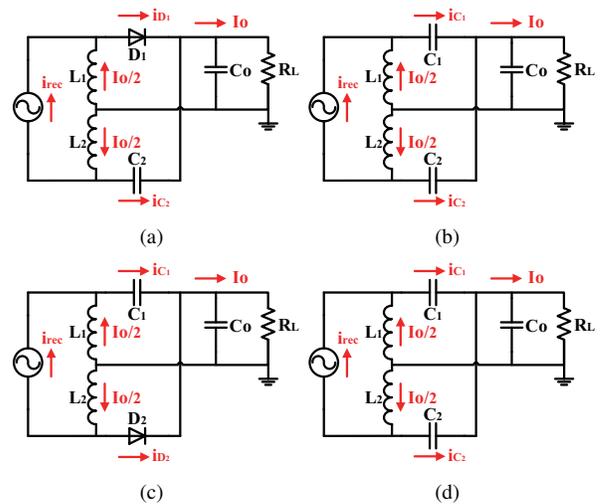


Fig. 2. Operating modes of Class E full-wave rectifier. (a)  $D_1$  on and  $D_2$  off. (b)  $D_1$  off and  $D_2$  off. (c)  $D_1$  off and  $D_2$  on. (d)  $D_1$  on and  $D_2$  on.

In the Class E full-wave rectifier,  $C$ , the capacitance of the two parallel capacitors, is the only parameter that needs to be

determined.  $C$  can be represented as follows [32]

$$C = \frac{1}{\omega R_L} \left[ \frac{1}{4\pi} - \frac{\pi}{2} (1-D)^2 + \frac{2\pi(1-D)\cos(\phi_{rec} + 2\pi D) - \sin\phi_{rec}}{4\pi\sin(\phi_{rec} + 2\pi D)} \right], \quad (1)$$

and

$$\tan\phi_{rec} = -\frac{\pi(1-D)\sin(2\pi D) + \sin^2(\pi D)}{\pi(1-D)\cos(2\pi D) + \sin(\pi D)\cos(\pi D)}, \quad (2)$$

where  $\omega$  is the operating frequency.  $D$  is the duty cycle of the two diodes and  $\phi_{rec}$  is the initial phase of  $i_{rec}$ . It can be seen from (1)(2) that  $D$  is determined by the values of  $C$  and  $R_L$  assuming a fix  $\omega$ . The Class E rectifier is usually designed to work at 50% duty cycle for a maximized power output capability. However, for the Class E full-wave rectifier, the overlapping of the diode conduction occurs when  $D \geq 0.5$ , i.e.,  $D_1$  and  $D_2$  are both turned on at the same time. Since the capacitors,  $C_1$  and  $C_2$ , are shorted out during the overlapping, the full-wave rectifier simply works as a hard-switching-based rectifier. This leads to higher harmonic contents and lower efficiency of the rectifier. Thus, in this paper, the maximum duty cycle of the diodes is chosen as 0.49 to avoid the overlapping and maximize the power output capability of the rectifier. Fig. 3 shows the relationship between the normalized load resistance,  $\omega CR_L$ , and duty cycle,  $D$ . It can be seen that a smaller  $R_L$  will lead to a higher  $D$  when  $\omega$  and  $C$  are fixed. In order to have  $D$  smaller than 0.49,  $C$  should be determined by the minimum target value of  $R_L$ ,  $R_{L,min}$ . Thus the optimal  $C$ ,  $C_{opt}$ , can be calculated by letting  $D = 0.49$  and  $R_L = R_{L,min}$  in (1)(2),

$$C_{opt} = \frac{0.1756}{\omega R_{L,min}}. \quad (3)$$

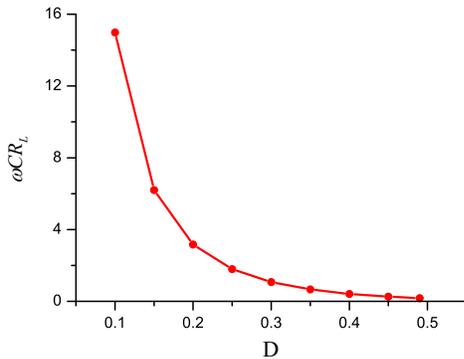


Fig. 3. Diode duty cycle,  $D$ , versus the normalized load resistance,  $\omega CR_L$ .

In order to optimize the overall MHz WPT systems, it is important to derive the input impedance of the Class E full-wave rectifier,  $Z_{rec}$ , which can be represented as

$$Z_{rec} = R_{rec} + jX_{rec}, \quad (4)$$

where  $R_{rec}$  is the resistance and  $X_{rec}$  is the reactance. Following the derivation procedure in [25], the input impedance

of the Class E full-wave rectifier is newly derived as follows assuming that the diodes and inductors are ideal components. Note the derived input impedance here is different from that of the full-wave rectifier derived in [32], where the rectifier is driven by two symmetrical current sources. The below input impedance of the rectifier serves as the basis for the following parameter design of the coupling coils and the Class E PA that maximizes the overall efficiency of the WPT system.

$$R_{rec} = \frac{2\sin(\phi_{rec} + 2\pi D)}{\pi\omega C_{opt}} \left[ \sin(\phi_{rec} + 2\pi D) - \sin\phi_{rec} + 2\pi(1-D)\cos\phi_{rec} + \frac{\cos\phi_{rec} - \cos(\phi_{rec} + 2\pi D)}{4\sin(\phi_{rec} + 2\pi D)} + \frac{\cos 2(\phi_{rec} + 2\pi D) - \cos 2\phi_{rec}}{\tan(\phi_{rec} + 2\pi D)} \right], \quad (5)$$

and

$$X_{rec} = -\frac{2\sin(\phi_{rec} + 2\pi D)}{\pi\omega C_{opt}} \left[ \cos\phi_{rec} + 2\pi(1-D)\sin\phi_{rec} - \frac{\sin\phi_{rec}}{\tan(\phi_{rec} + 2\pi D)} - \frac{\cos(\phi_{rec} + 2\pi D)}{2} + \frac{2\pi(1-D) + \sin\phi_{rec}\cos\phi_{rec}}{2\sin(\phi_{rec} + 2\pi D)} \right]. \quad (6)$$

### III. SYSTEM PARAMETER DESIGN

Here the parameter design procedure of an example 6.78 MHz WPT system is discussed and developed based on the input impedance of the rectifier derived in section II. Fig. 4 shows the circuit model of the WPT system, which includes a Class E PA, coupling coils, and the Class E full-wave rectifier. In the figure  $P_{in}$  is the input power of the PA,  $P_{Z_{in}}$  is the input power of coupling coils, and  $Z_{in}$  is the input impedance of coupling coils.

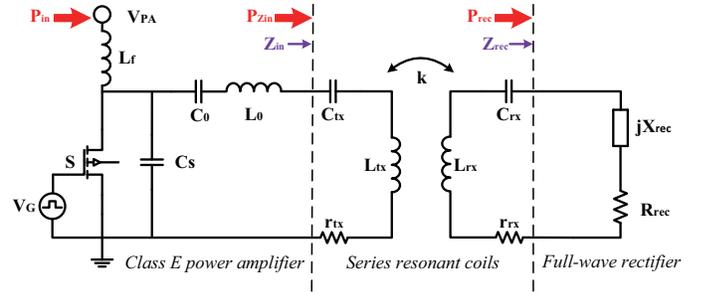


Fig. 4. Circuit model of the WPT system with  $Z_{rec}$ .

#### A. Coupling Coils

In the conventional WPT systems using the full-bridge rectifier, the coupling coils are compensated to be resonant at a target frequency by the compensation capacitors. However, the input reactance of the full-bridge rectifier is usually neglected because it is difficult to analytically derive the input impedance of the full-bridge rectifier. It is known that the input reactance of the rectifiers becomes obvious at MHz such as the full-bridge rectifier [12]. Thus the coupling coils are not accurately tuned to be fully resonant, which may affect the efficiency and

power transfer capability of the coupling coils. In this paper the derived input impedance of the full-wave rectifier, (5) and (6), is used to achieve a resonance exactly at a target frequency. The optimal compensation capacitors,  $C_{rx,opt}$  and  $C_{tx,opt}$ , should be determined following the below relationship,

$$j\omega L_{rx} + \frac{1}{j\omega C_{rx,opt}} + jX_{rec} = 0, \quad (7)$$

$$j\omega L_{tx} + \frac{1}{j\omega C_{tx,opt}} = 0, \quad (8)$$

where  $L_{tx}$  and  $L_{rx}$  are the inductances of the emitting and receiving coils, respectively, and  $\omega$  is the resonance/operating frequency of the WPT system, i.e., 6.78 MHz here. Then the optimal compensation capacitors can be expressed as

$$C_{rx,opt} = \frac{1}{\omega(\omega L_{rx} + X_{rec})}. \quad (9)$$

$$C_{tx,opt} = \frac{1}{\omega^2 L_{tx}}. \quad (10)$$

In addition, based on (7) and (8), and Fig. 4, the input impedance of coupling coils,  $Z_{in}$ , can be derived as

$$Z_{in} = r_{tx} + \frac{\omega^2 k^2 L_{tx} L_{rx}}{r_{rx} + R_{rec}}, \quad (11)$$

where  $k$  is the mutual inductance coefficient;  $r_{tx}$  and  $r_{rx}$  are the parasitic resistances of the transmitting and receiving coils, respectively. It can be seen that with the optimal compensation capacitors,  $C_{tx,opt}$  and  $C_{rx,opt}$ ,  $Z_{in}$  becomes pure resistive, and the compensation does not depend on the relative position of the coupling coils, i.e.,  $k$  [refer to (9) and (10)]. Note in real applications, due to the uncertainty in the value of the dc load,  $R_L$ , it is difficult to achieve such a desirable precise resonance. The above results are valid at a target operating point.

According to Fig. 4, the efficiency of the coupling coils is defined as

$$\eta_{coil} = \frac{P_{rec}}{P_{Z_{in}}}, \quad (12)$$

where  $P_{Z_{in}}$  is the input power of the transmitting coil and  $P_{rec}$  is the input power of the rectifier. The power loss occurs on the parasitic resistances of the coils, i.e.,  $r_{tx}$  and  $r_{rx}$ . Thus  $\eta_{coil}$  can be rewritten as

$$\eta_{coil} = \frac{Re\{Z_{in}\} - r_{tx}}{Re\{Z_{in}\}} \cdot \frac{R_{rec}}{r_{rx} + R_{rec}}, \quad (13)$$

where  $Re\{*\}$  means the real part of a complex number. Substituting (11) into (13) gives the efficiency of the coupling coils,

$$\eta_{coil} = \frac{\omega^2 k^2 L_{tx} L_{rx} R_{rec}}{(\omega^2 k^2 L_{tx} L_{rx} + r_{tx} r_{rx} + r_{tx} R_{rec})(r_{rx} + R_{rec})}. \quad (14)$$

The above equation can be further written as

$$\eta_{coil} = \frac{R_{rec}}{(1 + \frac{r_{tx} r_{rx} + r_{tx} R_{rec}}{\omega^2 k^2 L_{tx} L_{rx}})(r_{rx} + R_{rec})}. \quad (15)$$

Thus the efficiency of the coupling coils relates to the operating frequency  $\omega$ , the mutual inductance coefficient  $k$ , and the inductances of the coils,  $L_{tx}$  and  $L_{rx}$ .  $k$  indicates the required

power transfer distance and the coil misalignment. Larger the transfer distance and coil misalignment, lower  $k$ . Meanwhile, the size of a coil is mainly determined by its inductance. Smaller the size of the coils, smaller  $L_{tx}$  and  $L_{rx}$ . As shown in (15), with a higher  $\omega$ , a same coil efficiency can be maintained using smaller size coils, i.e., smaller  $L_{tx}$  and  $L_{rx}$ . Under the parameters in Table I, the efficiencies of the coupling coils are calculated and shown in Fig. 5 when sweeping  $k$  at different operating frequencies, 1, 3, and 6.78 MHz. Note for the sake of simplicity the parameters in Table I are assumed to be constant in the calculation. As same as predicted by (15), under the 6.78 MHz operating frequency a same efficiency such as 87% in the figure can be maintained under a small  $k$  ( $=0.10$ ), namely a long transfer distance and/or a large coil misalignment. Overall, a high operating frequency such as several MHz can help to reduce the size and weight of the WPT systems as well as achieve a high level of spatial freedom in terms of the power transfer distance and the tolerance to the coil misalignment [2], [8].

TABLE I  
PARAMETERS IN COIL EFFICIENCY CALCULATION.

$R_{rec}$	$r_{tx}$	$r_{rx}$	$L_{tx}$	$L_{rx}$
30 $\Omega$	0.8 $\Omega$	0.8 $\Omega$	3.34 $\mu H$	3.34 $\mu H$

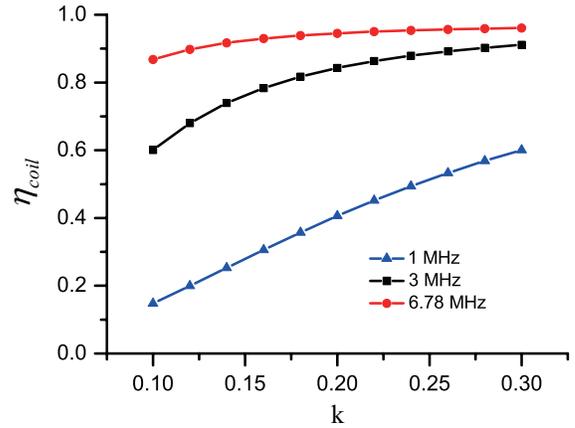


Fig. 5. Efficiency of the coupling coils versus  $k$ .

## B. Power Amplifier

In the WPT system the coupling coils are driven by a Class E PA. As shown in Fig. 4, it consists of a dc supply  $V_{PA}$ , a RF choke  $L_f$ , a switch  $S$ , a shunt capacitor  $C_S$ , a series capacitor  $C_0$ , and a series inductor  $L_0$ . Here  $C_S$  and  $C_0$  are the design parameters for the Class E PA, and  $L_f$  should be sufficiently large such that the ac current will not flow through it. In order to achieve zero-voltage switching (ZVS) and maximize the PA efficiency, it is known that (16) and (17) can be used to determine  $C_S$  and  $C_0$  [37],

$$C_S = \frac{0.1836}{\omega Z_{in}}. \quad (16)$$

$$C_0 = \frac{1}{\omega^2 L_0 - 1.1525\omega Z_{in}}. \quad (17)$$

Substituting the derived  $Z_{in}$ , (11), into (16) and (17) gives the optimal design parameters of the Class E PA,

$$C_{S,opt} = \frac{0.1836(R_{rec} + r_{rx})}{\omega(r_{tx}r_{rx} + R_{rec}r_{tx} + \omega^2k^2L_{tx}L_{rx})}, \quad (18)$$

and

$$C_{0,opt} = \frac{R_{rec} + r_{rx}}{(\omega^2L_0 - 1.1525\omega r_{tx})(R_{rec} + r_{rx}) - 1.1525\omega^3k^2L_{tx}L_{rx}},$$

respectively. As shown in the equations,  $C_{S,opt}$  and  $C_{0,opt}$  are determined by  $R_{rec}$  and  $k$ . And according to (1)-(5),  $R_{rec}$  itself relates to  $R_L$  and  $C_{opt}$ . Thus an optimal operation of the Class E PA depends on the values of  $R_L$ ,  $C_{opt}$ , and  $k$ , namely a system level optimization. Note as discussed above,  $C_{tx}$ ,  $C_0$ ,  $L_{tx}$ , and  $L_0$  at the transmitting side are all independent parameters in order to facilitate the component-level analysis and discussion.

#### IV. PERFORMANCE ANALYSIS AND COMPARISON

Here the performance of the Class E full-wave rectifier in the 6.78 MHz WPT system is analyzed and compared with that of the conventional full-bridge rectifier. A well-known radio frequency (RF) simulation tool, advanced design system (ADS) from Agilent, is used to investigate and compare the performances of the two rectifiers. The Pspice models of diode STPSC406 and MOSFET SUD06N10 are used in the simulation. The optimal parameters derived above are applied when using the Class E full-wave rectifier, while for the WPT system using the full-bridge rectifier, the compensation capacitors,  $C_{tx}$  and  $C_{rx}$ , are determined as 165 pF through the conventional design approach, i.e.,

$$j\omega L_{rx} + \frac{1}{j\omega C_{rx}} = 0. \quad (19)$$

$$j\omega L_{tx} + \frac{1}{j\omega C_{tx}} = 0. \quad (20)$$

Note unlike the Class E full-wave rectifier, it is challenging to analytical derive the input impedance of the full-bridge rectifier, which makes the optimized design and analytical calculation difficult.

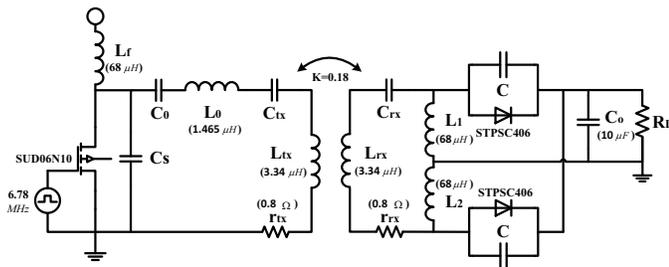


Fig. 6. Circuit model of the 6.78 MHz WPT system using the Class E full-wave rectifier.

For the 6.78 MHz WPT system in Fig. 6, its optimal design parameters,  $C$ ,  $C_{rx}$ ,  $C_{tx}$ ,  $C_S$ , and  $C_0$  are calculated using (3), (9), (10), (18) and (19), respectively. The calculated results for an example dc load,  $R_L (=30 \Omega)$ , are listed in Table II,

where  $R_{L,min}$  is assumed to be  $10 \Omega$ . In the following simulation the performances of the Class E full-wave rectifier are investigated in detail including total harmonic distortion (THD), waveforms of the input voltage/current, efficiency and power factor, diode voltage/current stress, and voltage/current transfer function. Note the results when using the conventional full-bridge rectifier are also co-listed for comparison purposes. In the following simulation and experiments, the two rectifiers, the Class E full-wave and full-bridge rectifiers, use same diodes (STPSC406), as listed in Fig. 6.

TABLE II  
OPTIMAL PARAMETERS WHEN  $R_L (=30 \Omega)$  AND  $k (=0.18)$ .

$D$	$C$	$C_{rx}$	$C_{tx}$	$C_S$	$C_0$
0.375	412 pF	265 pF	165 pF	187 pF	655 pF

#### A. Total Harmonic Distortion

Because the coupling coils and the Class E PA are originally designed to operate at resonance, the harmonic component of the input voltage/current of the rectifiers not only causes harmonic losses and heating problem in the receiving coil but also affects the performance and efficiency of both the coupling coils and the PA [33]. In addition, it causes poor EMI performance and thus adversely affects the operation of other nearby electronic devices. The input voltage/current total harmonic distortion (THD) of the rectifier can be used to evaluate the impact of rectifying operation on the signal quality of the WPT system. Due to the series resonant topology of the coupling coils here, the input current of the Class E full-wave current-driven rectifier is sinusoidal. Thus the input voltage total harmonic distortion of the rectifier is investigated and compared with the full-bridge rectifier in the MHz WPT system. Here THD is defined as

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} v_{rec,n}^2}}{v_{rec,1}}, \quad (21)$$

where  $v_{rec,1}$  is the fundamental component of the input voltage at the resonant frequency and  $v_{rec,n}$  represents the N-order input voltage harmonics.

As shown in Fig. 7(a), (b), (d), and (e), the input currents of the two rectifiers are sinusoidal. The input voltage of the Class E full-wave rectifier is close to an ideal sinusoidal wave, while the input voltage of the full-bridge rectifier is a square wave. Fig. 7(c) and (f) give the input voltage harmonic of the two rectifiers. It can be seen that the input voltage harmonic is much lower in the Class E full-wave rectifier than that in full-bridge rectifier. Note here only odd harmonics are shown for the two rectifiers due to the symmetrical topology. As shown in Fig. 7(c) and (f), the THD of the input voltage of the full-wave rectifier is 8.87%, about one fourth of the THD of the full-bridge rectifier, 37.5%. Using the Class E full-wave rectifier can significantly reduce the voltage harmonic contents in the MHz WPT system. In order to demonstrate the adverse influence of the diode conduction overlapping on

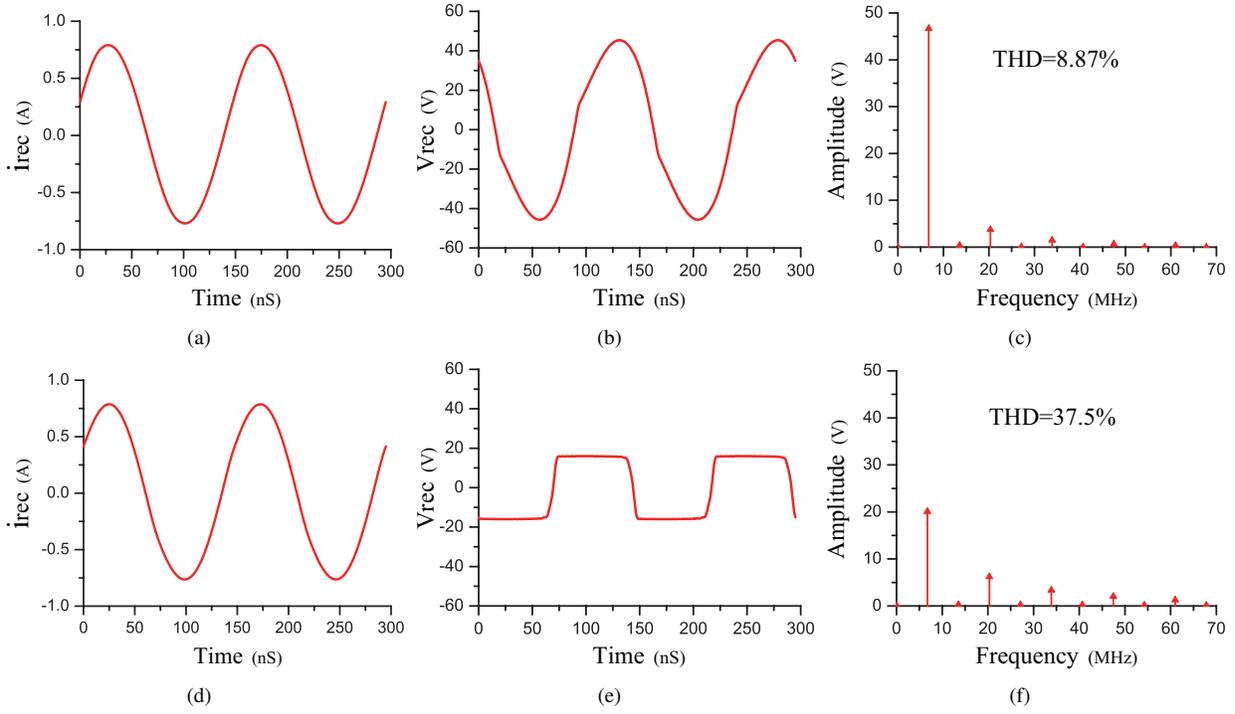


Fig. 7. Waveforms and harmonic contents. (a) Input current of the full-wave rectifier. (b) Input voltage of the full-wave rectifier. (c) Input voltage harmonic contents of the full-wave rectifier. (d) Input current of the full-bridge rectifier. (e) Input voltage of the full-bridge rectifier. (f) Input voltage harmonic contents of the full-bridge rectifier.

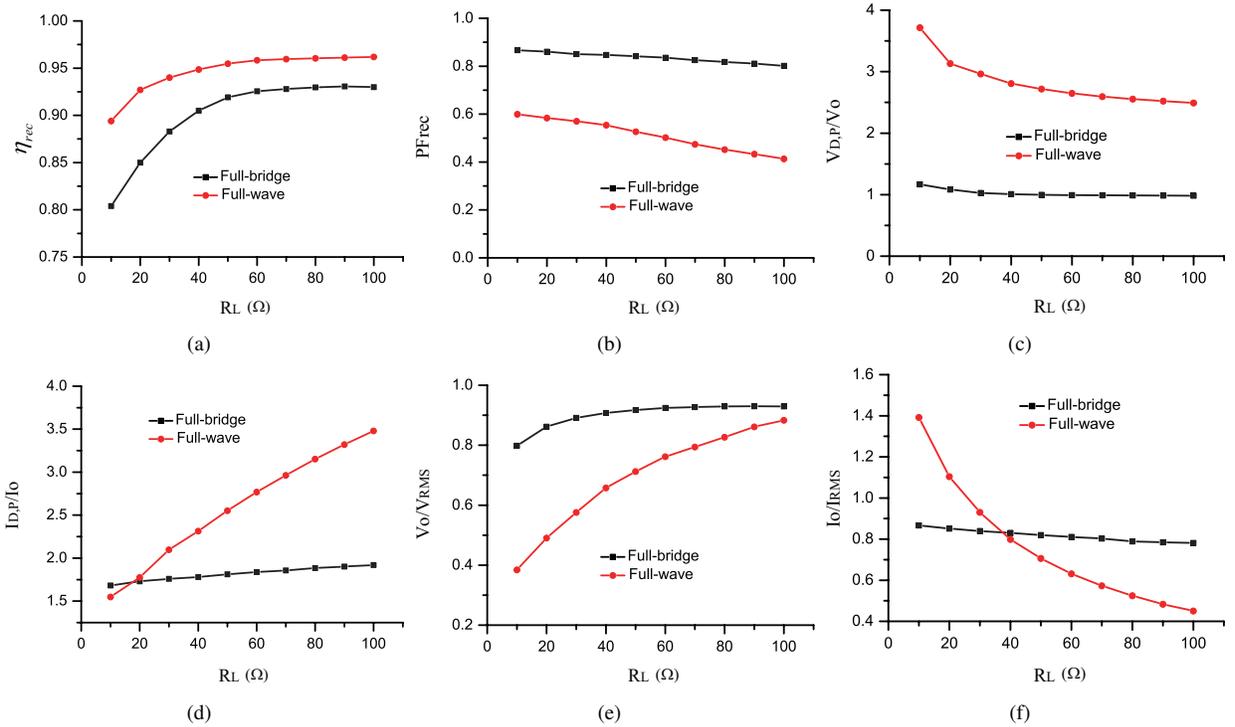


Fig. 8. Various parameters versus a varying  $R_L$ . (a) Efficiency. (b) Power factor. (c) Diode voltage stress. (d) Diode current stress. (e) Voltage transfer function. (f) Current transfer function.

the input voltage harmonic contents of the full-wave rectifier, Table III lists the input voltage THD of the rectifier when the overlapping occurs (duty cycle  $D > 0.5$ ). It can be seen that a higher  $D$ , i.e., higher overlapping, leads to a higher input

voltage THD. It is important to avoid the overlapping when using the full-wave rectifier, as discussed in section II.

TABLE III  
INPUT VOLTAGE THD WHEN  $D > 0.5$ .

$D$	0.52	0.54	0.56	0.58	0.6
THD	13.7%	15.3%	19.7%	23.1%	27.8%

### B. Efficiency and Power Factor

According to Fig. 1, the efficiency of the rectifier can be defined as

$$\eta_{rec} = \frac{P_o}{P_{rec}}, \quad (22)$$

where  $P_o$  is the dc output power of the WPT system and  $P_{rec}$  is the input power of the rectifier. The efficiencies of the Class E full-wave rectifier and the full-bridge rectifier are given in Fig. 8(a) when  $R_L$  is swept from 10 to 100  $\Omega$ . The efficiency of the Class E full-wave rectifier is higher than that of the full-bridge rectifier over a wide range of  $R_L$ . Due to the soft-switching technique, the diodes in the Class E full-wave rectifier are turned on and off at a low  $dv/dt$  and thus with low switching losses. In addition, since the waveforms of the current through the parallel combinations of  $C_1$ - $D_1$  and  $C_2$ - $D_2$  are the same sinusoidal waveforms and with 180° out of phase, the ac component in the output current is theoretically zero. This results in a nearly zero loss in the equivalent series resistance (ESR) of the filter capacitor,  $C_0$  in Fig. 1. Furthermore, the lower THD in the input voltage also indicates lower harmonic power loss. All the above advantages lead to a higher efficiency of the Class E full-wave rectifier over the conventional full-bridge rectifier.

The power loss breakdown for the Class E full-wave and full-bridge rectifiers are given in Table IV. For a fair comparison, the dc supply voltage of the PA,  $V_{PA}$ , is tuned to provide a same 10 W input power to the both rectifiers (i.e.,  $P_{rec}$ ) when the target dc load  $R_L$  is 30  $\Omega$ .  $P_{sw}$  and  $P_{cd}$  are the switching loss and the diode conduction loss in two rectifiers, respectively.  $P_L$  is the loss from the two 68  $\mu\text{H}$  dc filter inductors,  $L_1$  and  $L_2$ , in the full-wave rectifier. The power losses in the full-wave rectifier are calculated using the below equations, simulated dc output current  $I_o$ , and diode currents,  $i_{D_1}$  and  $i_{D_2}$  [refer to Fig. 2],

$$P_L = 2 \left( \frac{I_o}{2} \right)^2 r_L, \quad (23)$$

$$P_{cd} = \frac{1}{2\pi} \left\{ \int_0^{2\pi D} [V_F i_{D_1}(\omega t) + r_D i_{D_1}^2(\omega t)] d\omega t + \int_{2\pi(1-D)}^{2\pi} [V_F i_{D_2}(\omega t) + r_D i_{D_2}^2(\omega t)] d\omega t \right\}, \quad (24)$$

$$P_{sw} = P_{rec} - P_o - P_L - P_{cd}, \quad (25)$$

where  $P_o$  is the dc output power of the WPT system;  $P_{rec}$  is the input power of the rectifier;  $r_L$  ( $= 0.2 \Omega$ ) is the ESR of the dc filter inductors,  $L_1$  and  $L_2$ ;  $V_F$  ( $= 1.2 \text{ V}$ ) is the forward voltage drop of the diodes, and  $r_D$  ( $= 0.3 \Omega$ ) is the

on-resistance of the diodes. The power losses in the full-bridge rectifier can be similarly calculated,

$$P_{cd} = \frac{1}{2\pi} \left\{ 2 \int_0^\pi [V_F i_{D_1}(\omega t) + r_D i_{D_1}^2(\omega t)] d\omega t + 2 \int_\pi^{2\pi} [V_F i_{D_2}(\omega t) + r_D i_{D_2}^2(\omega t)] d\omega t \right\}, \quad (26)$$

$$P_{sw} = P_{rec} - P_o - P_{cd}. \quad (27)$$

Here  $i_{D_1}$  and  $i_{D_2}$  are the diode currents at positive- and negative-half cycles, respectively. As shown in Table IV, the switching loss of the full-wave rectifier is lower than that of the full-bridge rectifier due to its low  $dv/dt$  switching. It is interesting to note that the conduction loss of the full-wave rectifier is also smaller. This is because the two diodes in the full-wave rectifier are not turned on at the same time, while in the full-bridge rectifier two diodes are simultaneously turned on for the rectification, thus a higher conduction loss occurs in the full-bridge rectifier. The power loss from the inductors in the full-wave rectifier is much smaller than the switching and conduction losses because the currents through the inductors,  $L_1$  and  $L_2$ , are the dc current  $I_o/2$  and ESRs of the two dc filter inductors are very small. Therefore the full-wave rectifier achieves a higher efficiency than that of the full-bridge rectifier even there is an additional power loss from the dc filter inductors,  $L_1$  and  $L_2$ .

TABLE IV  
LOSS BREAKDOWN OF RECTIFIERS IN SIMULATION (RECTIFIER INPUT POWER  $P_{rec} = 10 \text{ W}$ ; DC LOAD  $R_L = 30 \Omega$ ).

Loss	Full-wave Rec.	Full-bridge Rec.
$P_{sw}$	0.28 W	0.61 W
$P_{cd}$	0.29 W	0.59 W
$P_L$	0.03 W	-

The power factor can be used as an indication to show how reactive a circuit is to a power source. Since the output current of the series resonant receiving coil is sinusoidal, the power factors of the Class E full-wave rectifier and the full-bridge rectifier can be both expressed as follows in WPT systems,

$$PF_{rec} = \frac{P_{rec}}{I_{RMS} V_{RMS}} = \frac{\sqrt{2} P_{rec}}{I_m V_{RMS}}, \quad (28)$$

where  $I_{RMS}$  and  $V_{RMS}$  are the RMS of the input current and input voltage of the two rectifiers, and  $I_m$  is the amplitude of the input current. As shown in Fig. 8(b), the power factors of the two rectifiers both decrease with an increasing  $R_L$ . Note the power factor of the Class E full-wave rectifier is lower, but still larger than 0.4.

TABLE V  
 $PF_{dist}$  AND  $PF_{disp}$  OF RECTIFIERS IN SIMULATION ( $R_L = 30 \Omega$ ).

Power Factor	Full-wave Rec.	Full-bridge Rec.
$PF_{dist}$	0.996	0.936
$PF_{disp}$	0.573	0.909

It is known that the power factor can also be represented as

$$PF = PF_{dist} \cdot PF_{disp}, \quad (29)$$

Where  $PF_{dist}$  is the distortion power factor and  $PF_{disp}$  is the displacement power factor [38]. As shown in Table V, the full-wave rectifier is superior in the distortion power factor, while its smaller displacement power factor due to the larger reactance lowers the overall power factor of the rectifier [refer to Fig. 10(c)]. Again in order to compensate the large reactance of the Class E full-wave rectifier, system-level analysis and design are important to improve the efficiency and power transfer capability of the overall MHz WPT system [refer to section III].

### C. Voltage/Current Stress and Transfer Function

The ratio of the diode peak voltage/current to the output voltage/current ( $V_{D,P}/V_o$  and  $I_{D,P}/I_o$ ) can be used to evaluate the voltage/current stresses of the diodes, which are shown in Fig. 8(c) and (d), respectively. As shown in the subfigures,  $V_{D,P}/V_o$  and  $I_{D,P}/I_o$  of the Class E full-wave rectifier are higher than those of the full-bridge rectifier over a wide range of the load, which are caused by the sinusoidal input voltage in the full-wave rectifier. At the same time, the sinusoidal input voltage contributes to the lower harmonic contents in the full-wave rectifier and the overall WPT system. There is a trade-off between the low harmonic contents and voltage/current stresses.

The voltage/current transfer functions are other important indices of the rectifiers to show the voltage/current gains from ac to dc. They are defined as the ratio of the output voltage/current of the rectifiers to the RMS of input voltage/current ( $V_o/V_{RMS}$  and  $I_o/I_{RMS}$ ). Fig. 8(e) and (f) show the voltage/current transfer functions of the two rectifiers. It can be seen that the full-wave rectifier has a lower voltage transfer function than that of the full-bridge rectifier, and the current transfer function of the full-wave rectifier decreases when  $R_L$  increases. The lower voltage transfer function corresponds to a lower voltage gain of the full-wave rectifier. This may enable the dc load to be directly driven by the rectifier without the need of the step-down dc/dc conversion.

## V. EXPERIMENTAL RESULTS

A 10 W 6.78 MHz WPT system is built up to validate the previous analysis and design of the Class E full-wave current-driven rectifier, coupling coils, and the Class E PA, as shown in Fig. 9. Its configuration is as same as the circuit model in Fig. 6, and the design parameters in Table II are applied. In the experimental system STPSC406 is used as the rectifying diode  $D_r$ , and SUD06N10 is for the switch of the PA. The parasitic capacitor of STPSC406 is assumed to be constant, 35 pF, according to the datasheet, because the diode operates at a peak voltage around 60 V. Note again the experimental results of the Class E full-wave rectifier and the full-bridge rectifier are both obtained when operating in the experimental WPT system. As shown in Fig. 9, the relatively large areas of the footprints in the coils are reserved for different connections of the discrete capacitors required in various experiments. In a final product, the areas can be largely reduced for a specific target application.

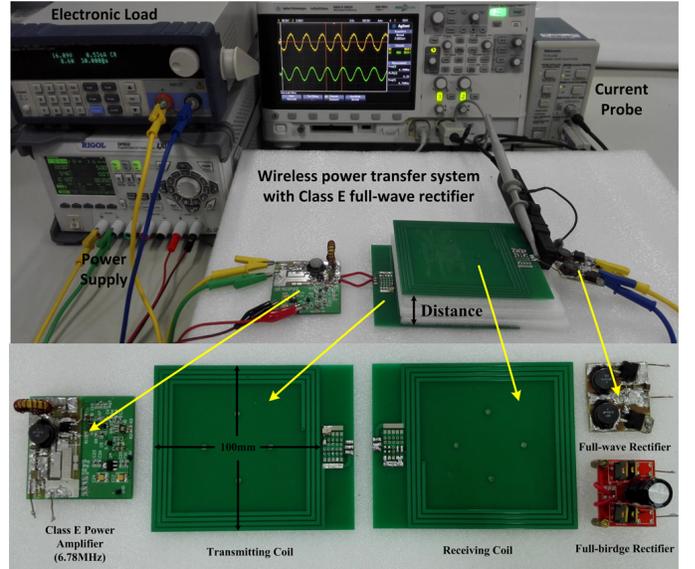


Fig. 9. The experimental setup of a 6.78 MHz WPT system.

Fig. 10(a) shows the duty cycle of the Class E full-wave rectifier with the fixed  $C$ , 412 pF in Table II, and a varying load  $R_L$ . The duty cycle decreases from 0.493 to 0.283 when  $R_L$  increases from 10 to 100  $\Omega$ . It validates the design of the rectifier to avoid the overlapping and maximize the power output capability, i.e., duty cycles around 0.5, over a wide range of load. Fig. 10 (b) and (c) give the experimental results, resistance and reactance, of the input impedance of the full-wave rectifier. The measured data is obtained through the fast Fourier transform (FFT) of the raw data from the oscilloscope. In the above subfigures the calculated results are also added, which well match the experimental results.

The experimental waveforms, harmonic contents, efficiency, power factor, diode voltage/current stresses, and voltage/current transfer functions of the Class E full-wave and conventional full-bridge rectifiers are shown in Figs. 11 and 12. The experimental results well match the simulation results in Figs. 7 and 8, and thus validate the previous theoretical analysis (the results in Fig. 8 are added in Fig. 12 for comparison purposes). As same as in simulation, the Class E full-wave rectifier shows higher efficiency over the full-bridge rectifier, while the power factor of the full-wave rectifier defined in (28) ( $> 0.4$ ) is lower than that of the full-bridge rectifier. In the experiments the efficiency and the power factor of the two rectifiers are calculated based on the voltage and current measurements. In order to achieve a high-accuracy measurement, the voltage and current probes are calibrated for a same phase at 6.78 MHz. Again due to the sinusoidal input voltage, the diode voltage/current stresses in full-wave rectifier are higher. However, the THD, 9.92%, of the full-wave rectifier is much lower than that of the conventional full-bridge rectifier, 42.2%. This advantage helps to improve the efficiency and EMI performance of the WPT system in real applications. In addition, as shown in Fig. 12(e), the voltage gain of the full-wave rectifier is lower than that of the full-bridge rectifier. This indicates the full-wave rectifier is possible

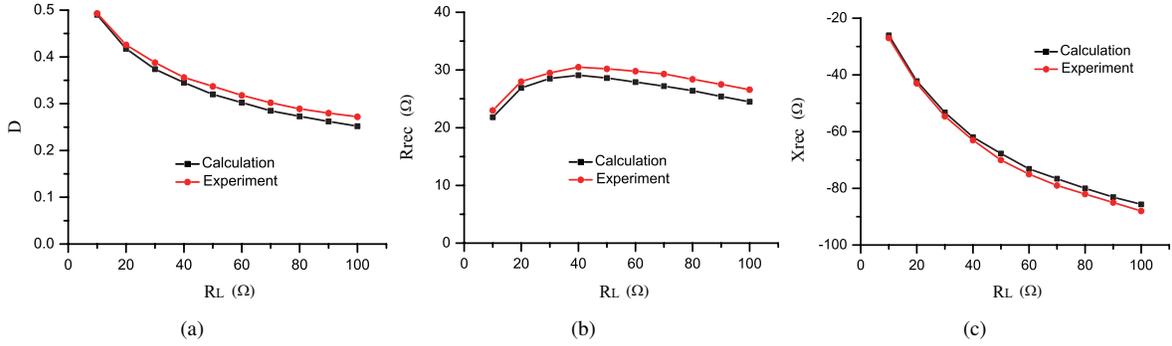


Fig. 10. Diode duty cycle and input impedance of the Class E full-wave rectifier. (a) Duty cycle. (b)  $R_{rec}$ . (c)  $X_{rec}$ .

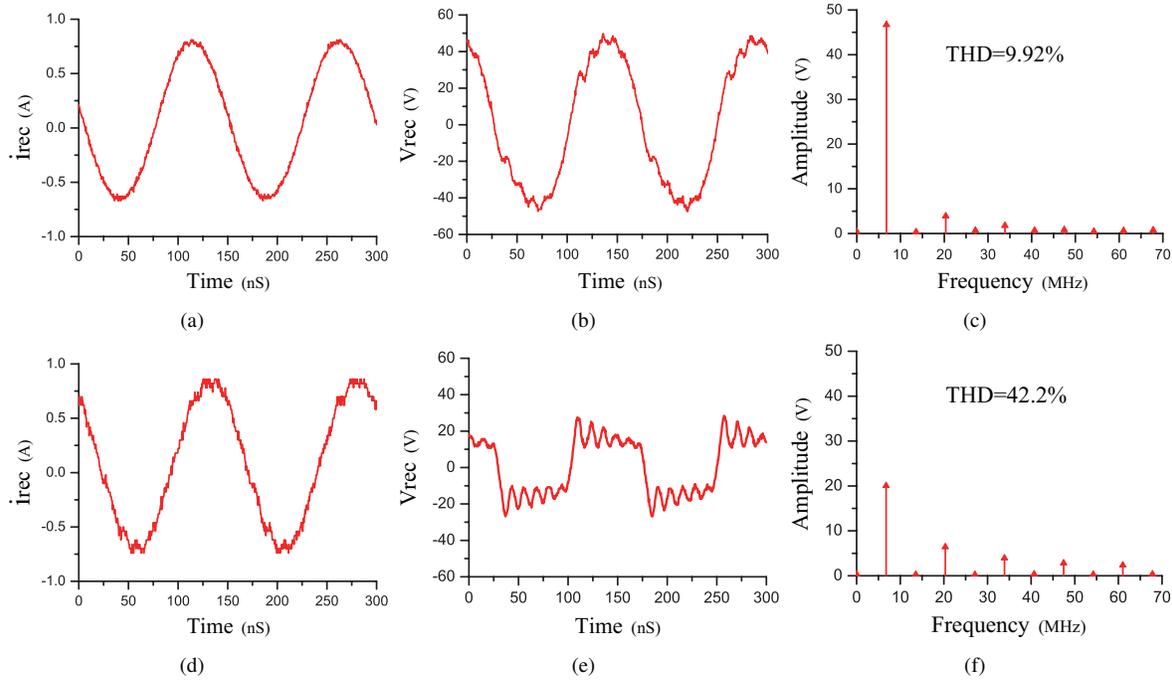


Fig. 11. Waveforms and harmonic contents (a) Input voltage of full-wave rectifier. (b) Input current of full-wave rectifier. (c) Voltage harmonic contents of full-wave rectifier. (d) Input voltage of full-bridge rectifier. (e) Input current of full-bridge rectifier. (f) Voltage harmonic contents of full-bridge rectifier.

to drive the load directly without using a buck converter.

In the present MHz WPT system, there are mainly four ac signals that largely affect the EMI performance of the final system, the input voltage/current of the transmitting coil and the output voltage/current of the receiving coil (i.e., the input voltage/current of the rectifier). Besides Fig. 11(c)(f), the THDs of the other three ac signals are further shown in Fig. 13(a)–(f). All the THDs are reduced by using the Class E full-wave rectifier. These THD measurements together indicate the improvement on the EMI performance of the overall MHz WPT system.

Table VI gives the experimental results on the loss breakdown of the full-wave and full-bridge rectifiers with a same 10 W input power of the rectifiers (i.e.,  $P_{rec}$ ), again for a fair component-level comparison, and a target  $R_L (= 30 \Omega)$ . (23)–(27) are used to calculate the losses, but the dc output current  $I_o$  and the diode currents,  $i_{D_1}$  and  $i_{D_2}$ , are the measured ones. Consistent with the simulation results and the analysis in section IV-B, the full-wave rectifier shows a higher efficiency

than that of the full-bridge rectifier.

TABLE VI  
LOSS BREAKDOWN OF RECTIFIERS IN EXPERIMENTS (RECTIFIER INPUT POWER  $P_{rec} = 10$  W; DC LOAD  $R_L = 30 \Omega$ ).

Loss	Full-wave Rec.	Full-bridge Rec.
$P_{sw}$	0.26 W	0.61 W
$P_{cd}$	0.29 W	0.60 W
$P_L$	0.03 W	-

Finally, for reference purposes, the system efficiencies of experiment and simulation,  $\eta_{sys}$ , versus  $R_L$  and  $k$ , are shown in Fig. 14(a)(b), respectively, for the WPT systems using the Class E full-wave rectifier and the full-bridge rectifier. Note the PA in the WPT system using the full-bridge rectifier is also optimized by (18) and (19). In the optimized design the full-bridge rectifier is assumed to be purely resistive, which is a common practice. Here  $V_{PA}$  is fixed as 22 V to achieve a 10 W power transfer under the target operating condition ( $R_L = 30 \Omega$  and  $k=0.18$ ). It can be seen that the WPT system using the

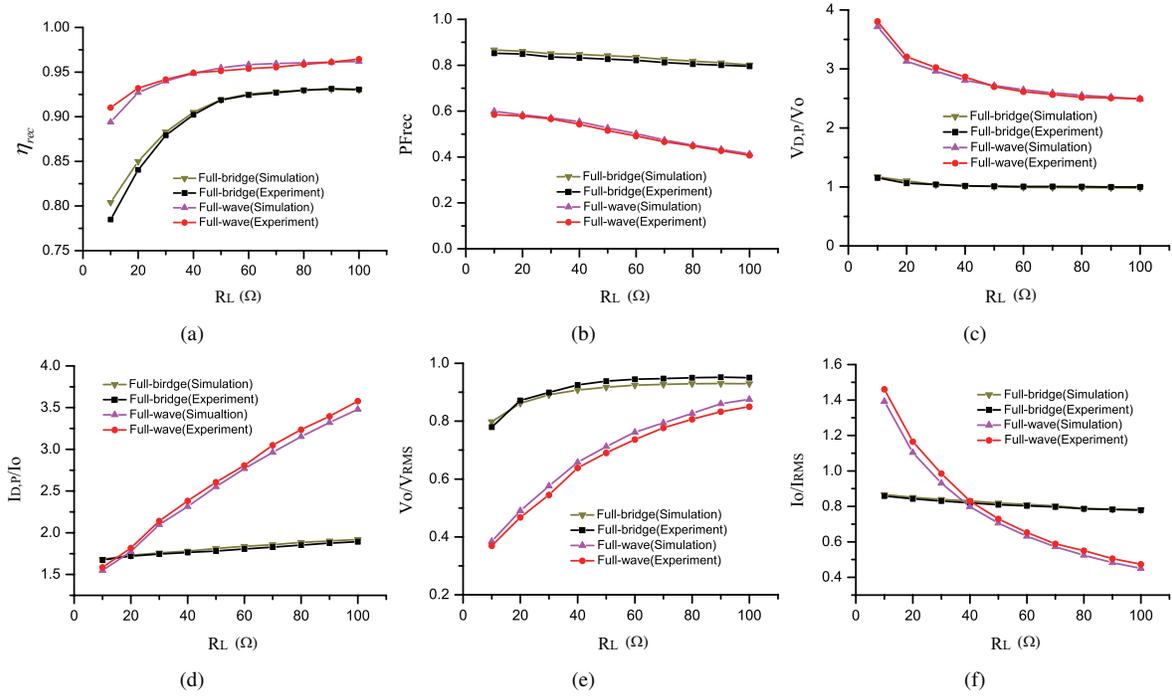


Fig. 12. Various parameters versus a varying  $R_L$ . (a) Efficiency. (b) Power factor. (c) Diode voltage stress. (d) Diode current stress. (e) Voltage transfer function. (f) Current transfer function.

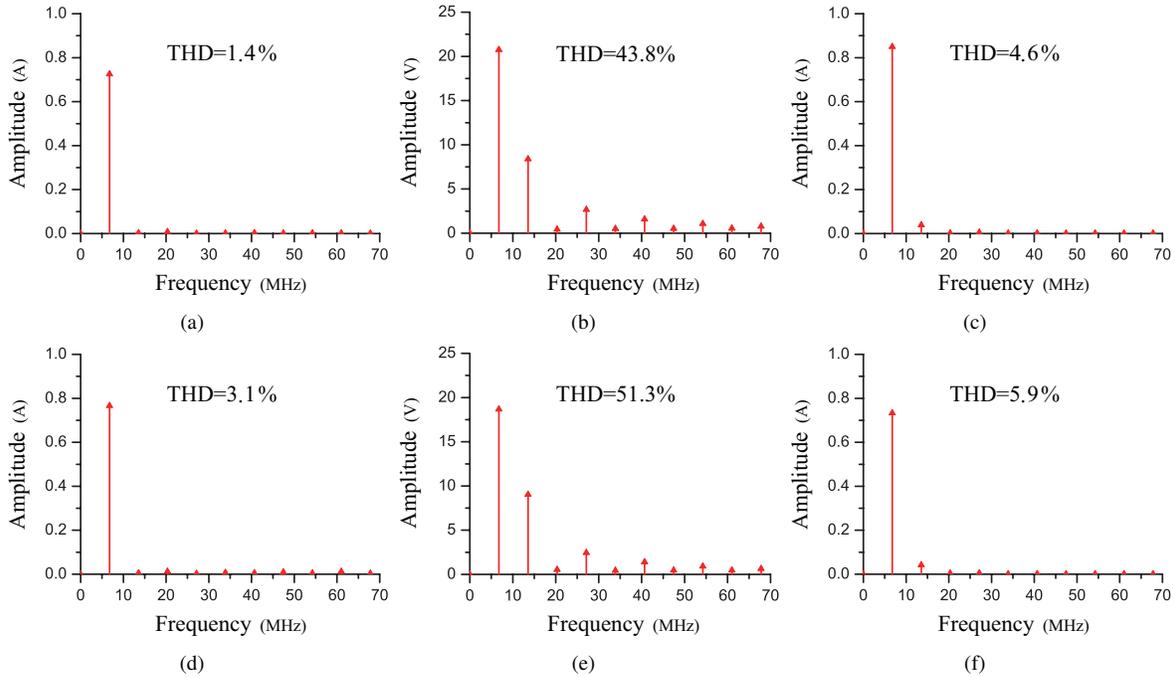


Fig. 13. Total harmonic distortions of the other three ac signals in the MHz WPT system. (a) Output current of the receiving coil using full-wave rectifier. (b) Input voltage of the transmitting coil using full-wave rectifier. (c) Input current of the transmitting coil using full-wave rectifier. (d) Output current of the receiving coil using full-bridge rectifier. (e) Input voltage of the transmitting coil using full-bridge rectifier. (f) Input current of the transmitting coil using full-bridge rectifier.

full-wave rectifier achieves a higher efficiency than the WPT system using the conventional full-bridge rectifier over a wide range of  $R_L$  and  $k$ . The loss breakdown of the two systems is also listed in Table VII. For a system-level comparison, the input power of the two WPT systems,  $P_{in}$ , are same 10 W under  $R_L = 30 \Omega$  and  $k = 0.18$ . Thus the rectifier input power

$P_{rec}$  are 9.25 W and 8.88 W in the systems using the full-wave and full-bridge rectifiers, respectively, which are different with the condition in the previous Table VI. Table VII shows that the power losses from the rectifiers significantly affect the overall system efficiency in the two 6.78 MHz WPT systems. This justifies the use of the soft-switching-based Class E full-

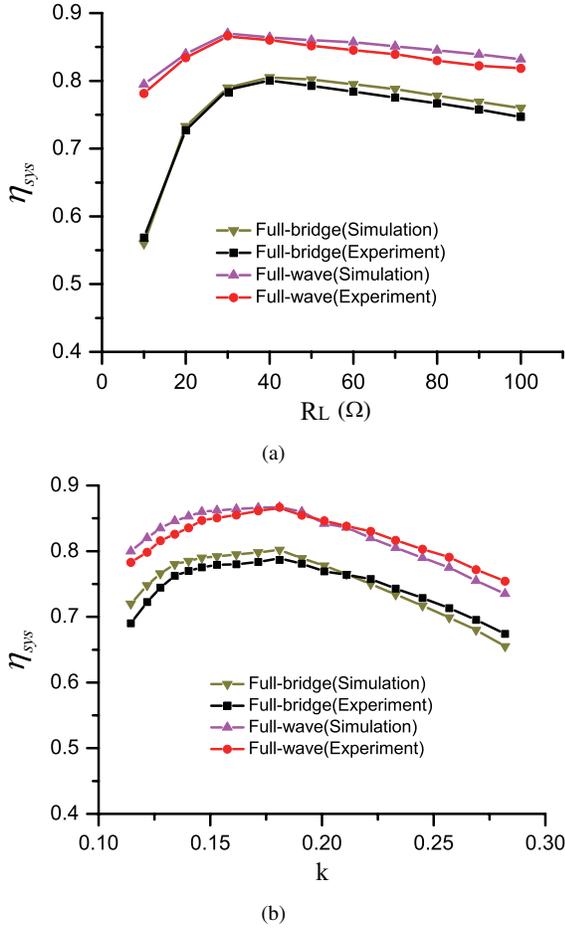


Fig. 14. Efficiencies comparison between the WPT systems using the proposed system design and the conventional design, respectively, when the Class E full-wave rectifier is used in both the WPT system. (a) Efficiencies versus  $R_L$ . (b) Efficiencies versus  $k$  (50–20 mm coil distances).

wave rectifier. It is especially interesting to note that the losses from the other components, the coupling coils and the PA, are also reduced in the WPT system using the full-wave rectifier, which validates the efforts of the system-level design and analysis discussed in this paper.

TABLE VII  
LOSS BREAKDOWN OF SYSTEMS IN EXPERIMENTS (SYSTEM INPUT POWER  $P_{in} = 10$  W; DC LOAD  $R_L = 30 \Omega$ ).

Loss	WPT system (Full-wave Rec.)	WPT system (Full-bridge Rec.)
Rectifier	0.55 W	1.06 W
Coupling Coils	0.33 W	0.55 W
PA	0.42 W	0.65 W
Total	1.30 W	2.26 W

## VI. CONCLUSIONS

This paper proposes the use of the Class E full-wave current-driven rectifier for a low-harmonic-contents and high-efficiency rectification in MHz WPT systems. Based on the input impedance of the rectifier, a design procedure is also developed to optimize the parameters of the Class E rectifier,

coupling coils, and the PA. Both the simulation and experimental results show the input voltage THD of the class E full-wave rectifier is significant reduced to one fourth of the THD of the conventional full-bridge rectifier. A high efficiency of the Class E full-wave rectifier, over 90%, is observed with a wide range of the load. The efficiency of the example 6.78 MHz WPT system is also improved to around 80% under a loosed coupling,  $k=0.18$ . The results in this paper demonstrate the promising aspects of the Class E full-wave rectifiers in harmonic contents reduction and efficiency improvement when being applied in MHz WPT systems.

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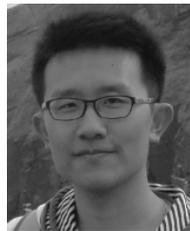
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