An Adaptive Reconfigurable Rectifier for Wireless Power Transmission

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***Abstract*—This letter presents a novel adaptive rectifier for wireless power transmission (WPT) applications. By utilizing a depletion-mode field-effect transistor (FET) switch, the configuration of the rectifier can automatically adapt to the input power level. Compared with traditional rectifiers, it can provide a consistent high RF-to-dc power conversion efficiency (PCE) over a significantly extended operating input power range. Measured results show that the PCE of this proposed adaptive rectifier keeps above 50% in the input power range spanning from −14 up to 21 dBm. Additionally, maximum PCE of more than 75% is achieved in the input power range from 5 to 15 dBm.**

***Index Terms*—Rectifier, switch, wireless power transmission (WPT).**

I. Introduction

RECENTLY, wireless power transmission (WPT) [1] has rapidly become a hot spot of research since it has several potential areas of application, such as supplying or recharging sensors for noninvasive monitoring systems, and powering smart actuators for vehicle systems.

The key component of WPT systems is the rectenna (rectifier and antenna), among which a rectifier is crucial to improve the transmission RF-to-dc power conversion efficiency (PCE). Considerable research has been placed on rectifiers using different kinds of topologies, for instance, diode in series [2], diode in shunt [3], diodes in bridge [4], diodes in voltage doubler [5], and so forth. However, as pointed out in [6], each of those rectifiers can only be designed for a narrow input power range in which the RF-to-dc PCE is satisfied. In contrast, the efficiency falls down very quickly at other input power levels. This becomes a key limitation for the wireless charging applications in which the input power level could change significantly since high efficiency over a wide input power range is required to considerably shorten the charging period. To overcome this limitation, a reconfigurable rectifier in [6] was designed to harvest RF power over a wide input power range. However, it introduces relatively complicated add-on switch components and detector circuits, which can be excessively troubling to design and fabricate for different operating frequencies.

In this letter, a simple adaptive rectifier which can operate over a wide input power range is presented. By combining two circuit topologies for low-input-power and high-input-power WPT applications respectively, and a FET switch, the rectifier can automatically reconfigure to the more favorable circuit topology depending on the input power level. Therefore, it can significantly extend the operating input power range where the high conversion efficiency is obtained. With simple structure and compact size, this novel rectifier can readily mate with antennas for future WPT applications.

Manuscript received October 25, 2012; revised January 11, 2013; accepted February 22, 2013. Date of publication March 15, 2013; date of current version August 30, 2013. The work was supported by the National Research Foundation, Singapore, under grant NRF2001 NRF-CRP001–057.

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Digital Object Identifier 10.1109/LMWC.2013.2250272

II. Operation Mechanism

It is well known that the diode's threshold voltage is critical to determine the rectifier's RF-to-dc PCE performance at low input power levels. When the threshold voltage of the diode is comparable to the amplitude of the incident RF power, a relatively large portion of input power is consumed to overcome the threshold voltage which leads to a low RF-to-dc PCE. Therefore, diodes with low threshold voltage are preferred for low-input-power applications. Meanwhile, as the input power level increases, the loss of the diode internal resistance gradually becomes dominant, which raises the efficiency in the high input power region. However, the efficiency sharply decreases as the voltage swings at the diode exceeds its breakdown voltage [7]. As a result, diodes with high breakdown voltage are more preferred for high-input-power applications.

As shown in Fig. 1(a), shunt mounted single diode rectifier is one of the simplest and most commonly used rectifier topologies. It has been proven that this topology has a high RF-to-dc PCE for low input power levels with careful tuning [3]. In this work, 100 MHz was chosen as the operating frequency due to the project related research requirement. However, its mechanism is not limited to this specific frequency point. It can be applied to other frequencies. In Fig. 1(a), a Schottky diode HSMS-2852 (breakdown voltage is 3.8 V) was adopted as D1 because of its low threshold voltage (150 mV). Resistor R1 (3 kΩ) is placed as the load to collect the converted dc power. The capacitor C1 matches the input impedance of the rectifier to 50 Ω and blocks the load dc voltage to the RF power source. The inductor L1 and capacitor C2 act as a dc-pass filter in front of the load. After advanced design system (ADS) optimization, the simulated efficiency of this rectifier with swept input power is depicted in Fig. 2 as Eff(a). It is clear that the efficiency continues to grow with increasing input power until it reaches a maximum of 85% at an input power of 0.3 dBm. However, when the input power surpasses this level, the efficiency decreases quickly since the voltage sways at the diode exceed the breakdown voltage. Thus, this rectifier only suits low-input-power WPT applications.

To raise the power handling capabilities of the rectifier, more shunt-mounted diodes are introduced in the second topology, shown in Fig. 1(b), where D2 denotes four Schottky diodes

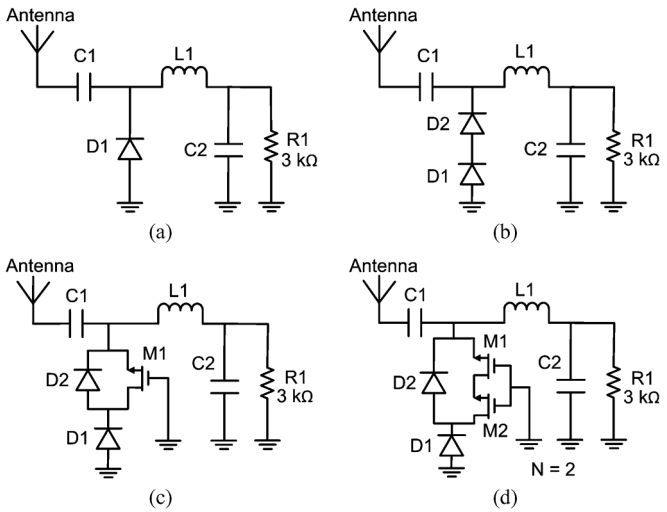


Fig. 1. Rectifier circuit topologies. (a) Single shunt-mounted diode. (b) Five shunt-mounted diodes. (c) Five shunt-mounted diodes with one FET as a switch. (d) Five shunt-mounted diodes with two FETs as a switch ($N = 2$).

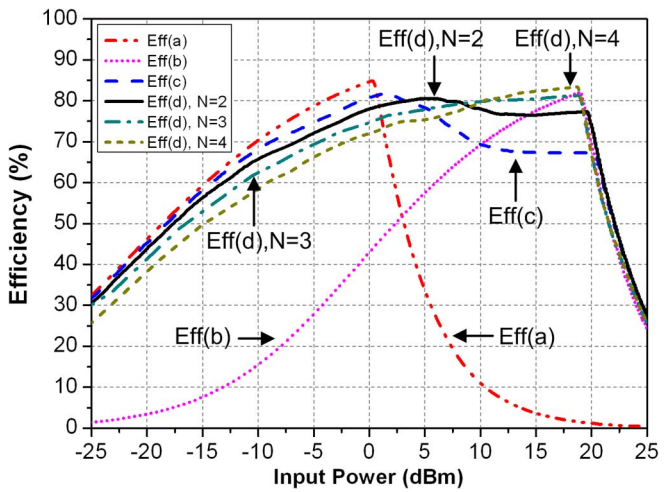


Fig. 2. Simulated efficiencies versus input power for the four different rectifier topologies shown in Fig. 1.

HSMS-2860 (threshold voltage is 350 mV, breakdown voltage is 7 V). The combination of diodes D1 and D2 have a higher breakdown voltage, hence this rectifier is able to handle high input power. Optimized efficiency of this rectifier is presented in Fig. 2 as Eff(b). It can be seen from Eff(b) that a peak efficiency of 82% is achieved at 19 dBm input power. However, the stack of D1 and D2 increases the total threshold voltage, which leads to poor efficiency for low input power levels. This problem could potentially be relieved if diodes with threshold voltage levels closer to 0 V [8], [9] are used as D2. But this solution requires advanced fabrication technologies and won't be discussed here. When the input power is less than -5 dBm, the efficiency remains lower than 30%. Therefore, this rectifier is only suitable for high-input-power WPT applications.

In order to extend the operating input power range of these two preceding rectifiers, a novel rectifier has been proposed in Fig. 1(c). Compared with that in Fig. 1(b), a FET is introduced in this topology as an adaptive switch. Here the M1 is an n-channel depletion-mode hetero-junction FET, NE3210S01 (threshold voltage is -0.7 V), which is connected in parallel with the diodes D2. The gate of M1 is grounded, hence its gate to source voltage (V_{gs}) is equal to the inverse output dc voltage

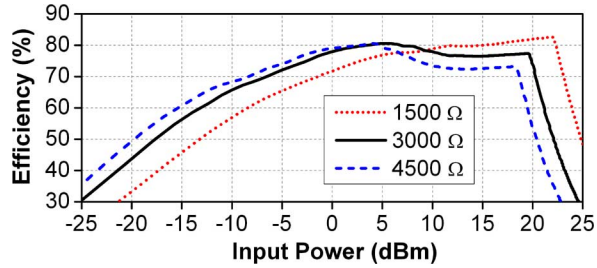


Fig. 3. Simulated efficiencies versus input power for the topology ($N = 2$) in Fig. 1(d) with different load resistances.

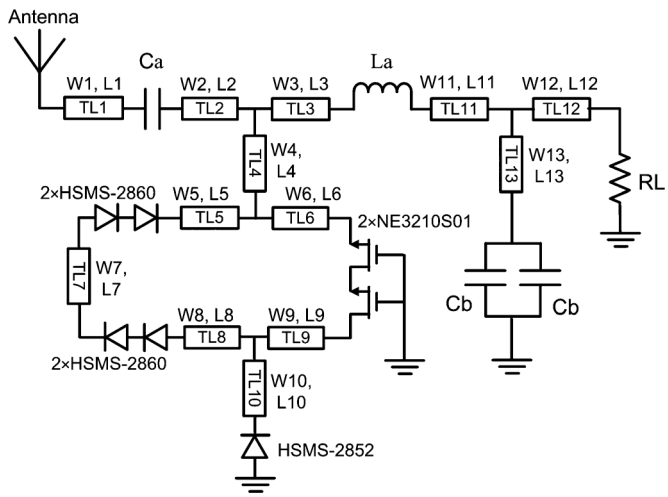
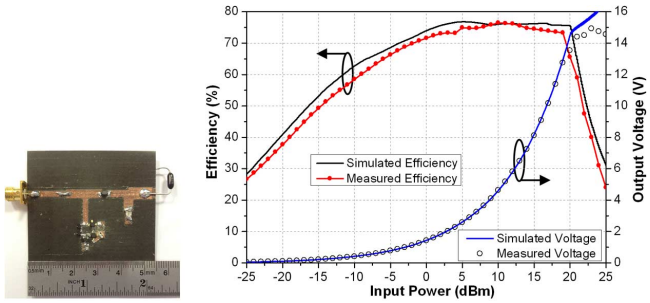


Fig. 4. Circuit configuration of the proposed rectifier. The parameters of the microstrip lines are: $W1 = 2.4$ mm, $L1 = 15$ mm, $W2 = W3 = 3.5$ mm, $L2 = L3 = 7.5$ mm, $W4 = 2$ mm, $L4 = 13$ mm, $W5 = W6 = W8 = W9 = 0.7$ mm, $L5 = L6 = L8 = L9 = 3$ mm, $W7 = 0.7$ mm, $L7 = 1.8$ mm, $W10 = 2$ mm, $L10 = 1$ mm, $W11 = 3$ mm, $L11 = 7$ mm, $W12 = 5$ mm, $L12 = 8$ mm, $W13 = 4$ mm, $L13 = 5$ mm. $RL = 2800\ \Omega$, $Ca = 5.1$ pF, $La = 290$ nH, $Cb = 100$ pF.

on the load R1. The optimized efficiency of this rectifier versus input power is plotted in Fig. 2 as Eff(c). At first, when the input RF power is low, V_{gs} of M1 is near 0 V, so this FET switch operates in the on-state. Diodes D2 are shorted by M1 under such low input power conditions and the rectifier would behave like the one in Fig. 1(a). Thus, it can be seen in Fig. 2 that Eff(c) matches Eff(a) well for input power lower than -15 dBm. Under high input power conditions, M1 operates in the off-state for almost all the time since the output dc voltage is high. But it turns on at the moment when the instantaneous voltage at the cathode of D2 is below absolute value of M1's threshold voltage. Thus, D2 can be shorted only when it is forward biased. In this way, a small threshold voltage and large breakdown voltage can be achieved for the combination of D1 and D2 at the same time. As a result, this rectifier reconfigures to the more efficient topology in accordance with input power level. Compared with the traditional ones in Fig. 1(a) and (b), this reconfigurable rectifier has greatly enlarged its operating input power range. It can be found in Fig. 2 that Eff(c) can remain above 50% for input power from -18.3 to 22 dBm. However, Eff(b) and Eff(c) differ when the input power range rises from 10 to 20 dBm. The degradation in PCE is caused by the breakdown of diode D1. This problem can be solved by an improved topology shown in Fig. 1(d), where two FETs are used instead of one. Therefore, the combination of M1 and M2 can achieve a better off-state in the range of input power between 3 and 20 dBm. The optimized efficiency



(a) (b)

Fig. 5. (a) Photograph of the fabricated rectifier. (b) Simulated and measured efficiencies and output voltages of the rectifier versus input power level.

TABLE I
PERFORMANCE COMPARISON

Reference	Technology	Topology	Freq (GHz)	P_{in} (dBm) range for PCE > 50%
[2]	PCB	Diode in series	1.5754	> -4 to 10
[3]	PCB	Diode in shunt	2.45	-17.2 to 6.5
[4]	PCB	Modified full-wave Greinacher	2.45	-14.5 to 3
[6]	0.18 µm CMOS	Combination of series, shunt and bridge	1.8	-4 to 30
This Work	PCB	Reconfigurable diodes in shunt	0.1	-14 to 21

of this improved reconfigurable rectifier is plotted in Fig. 2. It is worth noting that this improved rectifier topology can significantly enhance the efficiency in a wide input power range from 3 to 20 dBm.

Fig. 2 also shows the performances of the rectifiers with 3 and 4 FETs stacked in series. It can be seen that with more FETs, the efficiency tends to be higher in the high input power region and lower in the low input power region. The simulated efficiencies versus input power for the rectifier $(N = 2)$ in Fig. 1(d) with different load resistances are plotted in Fig. 3. It can be found that with larger resistance, the efficiency tends to be higher in the low input power region and lower in the high input power region. Thus, there's a tradeoff between the low and high input-power efficiencies for the selections of both the number of FETs and the load resistance. In addition, the selection of the threshold voltage of the FET must ensure that under high input-power conditions, the instantaneous V_{gs} will turn the FET off when the reverse biased voltage applied to diode D1 approaches its breakdown voltage.

III. Experimental Results and Discussion

A novel reconfigurable rectifier using microstrip lines is proposed based on the topology shown in Fig. 1(d). The circuit configuration with detailed optimized parameters is illustrated in Fig. 4. Fig. 5(a) shows the photograph of the fabricated rectifier, which uses a 31-mil-thick Rogers 5880 substrate.

In the measurement, by measuring the input RF power and the output dc voltage across the resistive load simultaneously, the RF-to-dc PCE can be obtained by

$$\eta(\%) = \frac{V_L^2}{R_L} \times \frac{1}{P_{in}} \times 100 \qquad (1)$$

where V_L is the measured output dc voltage on the resistor, R_L is the resistance value, and P_{in} is the input power level measured by the spectrum analyzer LG SA-990.

The simulated and measured efficiencies and output voltages of the rectifier versus input power level are depicted in Fig. 5(b). It can be seen that measured and simulated results agree with each other well. Measured efficiency of more than 50% was achieved over an enhanced input power range, from −14 to 21 dBm. In addition, an RF-to-dc PCE of above 75% was reached between 7 and 14 dBm. The output dc voltage reached 14.9 V with an input power of 23 dBm. These measured results prove that this reconfigurable rectifier topology could be profitably adopted in WPT applications where a wide operating input-power range is required.

In Table I, the performance of this work is compared with several recently published RF rectifiers. Direct comparison is made somewhat difficult because those rectifiers operate at different frequency points with different topologies and fabrication technologies. As indicated, the input power range for PCE more than 50% of this presented rectifier appears favorably in comparison with other designs.

IV. Conclusion

This letter proposed a method to extend the operating input-power range of a rectifier. It was demonstrated that the conversion efficiency of the proposed rectifier is greater than 50% for input power levels extending from −14 to 21 dBm. The RF-to-dc PCEs of WPT applications are usually limited by the narrow operating input-power range of traditional rectifiers, and this study offers an effective solution to this issue.

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