A High-efficiency Broadband Rectenna for Ambient Wireless Energy Harvesting

Chaoyun Song, Yi Huang, *Senior Member, IEEE*, Jiafeng Zhou, Jingwei Zhang, Sheng Yuan and Paul Carter

Abstract— **This paper presents a novel broadband rectenna for ambient wireless energy harvesting over the frequency band from 1.8 to 2.5 GHz. First of all, the characteristics of the ambient radio-frequency energy are studied. The results are then used to aid the design of a new rectenna. A novel two-branch impedance matching circuit is introduced to enhance the performance and efficiency of the rectenna at a relatively low ambient input power level. A novel broadband dual-polarized cross-dipole antenna is proposed which has embedded harmonic rejection property and can reject the 2nd and 3rd harmonics to further improve the rectenna efficiency. The measured power sensitivity of this design is down to -35 dBm and the conversion efficiency reaches 55% when the input power to the rectifier is -10 dBm. It is demonstrated that the output power from the proposed rectenna is higher than the other published designs with a similar antenna size under the same ambient condition. The proposed broadband rectenna could be used to power many low-power electronic devices and sensors and found a range of potential applications.**

Index Terms—**Rectenna, energy harvesting, broadband rectifier, cross dipole antenna, harmonic rejection.**

I. Introduction

WITH the explosive and rapid development of wireless technologies, the ambient wireless power density is growing since there is an increasing number of various electromagnetic power sources such as the cellular mobile base stations, digital TV towers and Wi-Fi routers. The idea of utilizing the radio-frequency (RF) energy to power low-power electronic devices has gained a lot of popularity in recent years in order to replace the battery and save maintenance cost. Wireless energy harvesting by using rectifying antenna (rectenna) technologies is a feasible solution to convert the ambient RF power to a usable DC power. Thus, a lot of progress has been made in the research of the rectenna, which is the most widely adopted device for the wireless power transmission (WPT) and energy harvesting over the past 10 years or so.

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Various designs, such as single-band rectennas and arrays [1]-[7], multi-band rectennas [8]-[12] and broadband rectenna arrays [13], have already been investigated and different antennas and rectifier designs have also been analyzed and summarized in such as [14] and [15]. The overall performance of a rectenna is normally determined by the performance of the antenna and the conversion efficiency of the rectifying circuit. A single narrow band design is conducive to achieve high efficiency but the amount of the DC output power is limited. A multiband, or a broadband design or a rectenna array can accumulate more power from the weak ambient sources and produce more output power than that from a narrow band rectenna, but the trade-offs might be a decreased overall efficiency and an increased dimension. At present, the main challenge of wireless energy harvesting is how to improve the power conversion efficiency at low-input power levels over a broad frequency band. There have been some approaches to improve the antenna performance using such as the polarization diversity [16]-[18]. The power conversion efficiency can be improved by using a filter between the antenna and the rectifier to reject the higher order harmonics generated by the non-linear rectifying circuit [19]. Some designs in such as [20] and [21] using an antenna-filter structure have embedded the harmonic-rejection property on the receiving antenna to replace a filter. Additionally, in order to handle the instability of ambient incident signals, the potential of utilizing an adaptive rectifier to match the dynamic input power level were discussed in [22] and [23]. Some researchers have conducted the field measurement survey in order to identify the frequency band and the power density of the ambient wireless energy [24], [25]. The measured frequency band was relatively broad (from 500 MHz to 3 GHz) and the difference in reported power levels was quite significant. In order to gain a better understanding of the ambient wireless energy, we have also conducted a field measurement campaign in the city centre area of Liverpool in the U.K. The frequency bands of interests are the cellular mobile radio and WLAN bands which are 800 – 960 MHz, 1790 – 1880 MHz, 2100 – 2170 MHz and 2380 – 2450 MHz. The measurement area is divided into three categories: *indoor scenario, outdoor scenario* and *semi-indoor scenario*. The highest average power density was found to be -7 dBm/m^2 at UMTS-2100 band in the outdoor scenario. The average power density varies between -35 dBm/m^2 and -10 dBm/m^2 in most scenarios. The detailed results can be found in [26].

It is found that most reported rectennas are not optimized for the ambient signal levels in reality. The desired input power levels for most of these designs are much higher than the

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ambient input power levels.

In this paper, we propose a novel broadband rectenna for RF energy harvesting which works well from 1.8 GHz to 2.5 GHz (to cover the United Kingdom GSM-1800/4G, 3G/UMTS-2100 and WLAN bands). The rectenna is designed and optimized for relatively low input powers (-35 dBm to -10 dBm) as we have found in our measurement campaign. This design is quite different from the conventional rectenna design in terms of the incident power level as well as the bandwidth. The power sensitivity is enhanced by a new rectifier circuit which is aimed to reduce the RF power consumption. In addition a novel impedance matching circuit is introduced to match the broadband rectenna with various low input power levels. The harmonic rejection property is embedded on the antenna to make the size more compact and improve the overall efficiency. The rectenna is fabricated and tested. The measured results show that the rectenna has good sensitivity at low input power levels. The minimum detectable input power level of this design is -35 dBm. With a similar input power level, our measured output DC power is higher than the other published results.

The rest of this paper is organized as follows. Section II explains the configuration of the rectenna includes the design of an improved broadband rectifier and the design of a broadband dual-polarization antenna with harmonic-rejection. Section III describes the experimental results of the rectenna. Finally, conclusions are drawn in Section IV.

II. Rectenna Design

In order to increase the output power from a rectenna, a novel broadband rectenna is proposed and shown in Fig. 1 with the optimized dimensions. A planar dual-polarized antenna is built on a low-cost FR4 substrate with relative permittivity of 4.4 and a thickness of 1.6 mm. The rectifying circuit is built on the Duroid 5880 substrate with relative permittivity of 2.2 and a thickness of 1.575 mm (shown in Fig. 1(a)). The antenna and the rectifier are linked by a 50 Ω microstrip line which is built on a FR4 board with an H-shaped slot filter on the ground plane. A flower-shaped slot filter is embedded on the antenna patch. Both filters are used to suppress the 2nd and 3rd order harmonics produced by the rectifier in order to improve the overall power conversion efficiency of the rectenna. The fabricated prototype is shown in Fig. 1(c) and (d). The overall dimension of the rectenna is 70 × 70 × 13.2 mm^3.

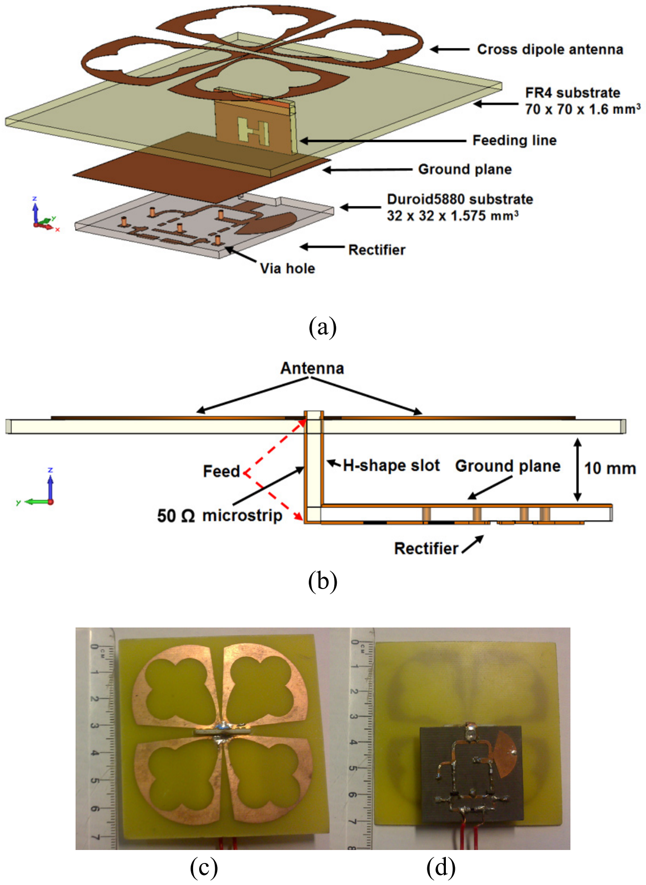

Fig. 1. (a) 3D model of the proposed rectenna. (b) Side view of the proposed rectenna. (c) Front side of the fabricated prototype. (d) Back side of the fabricated prototype.

A. *Rectifier design*

The rectifying circuit is a vital part of a rectenna since it decides the RF to DC conversion efficiency. A good rectifier must have a low power consumption, good power sensitivity and good power handling capability [27]. Normally, a rectifying circuit consists of an impedance matching circuit for delivering the maximum power, a rectifying element (diode) to perform the RF to DC conversion, a DC pass filter for smoothing the ripple of output DC and a load (resistor). A conventional single series diode rectifying circuit is depicted in Fig. 2. The RF power received by the antenna is attenuated passing through the impedance matching circuit and the diode. The remaining power is converted into the DC power. The capacitor C_1 acts as a high-pass filter and energy storage element. However, in this scenario only the positive half cycle of the wave can be rectified by the diode and the negative half cycle is rejected. The single series diode configuration (which is different from the single shunt diode configuration) is not efficient for ambient RF energy harvesting since the incident power density is relatively low which does not satisfy the biasing requirement of the circuit. Also, the breakdown voltage of the single diode rectifier is limited which could affect the power handling capability of the circuit. Thus, an improved configuration, a voltage doubler rectifier is proposed and shown in Fig. 3 which may also be considered as a modification of the single shunt diode configuration. The positive half cycle of the wave is rectified by the series diode D_1 and the energy is stored in C_1. The negative half cycle of the wave is rectified by the shunt diode D_2 and the energy is stored in C_2. The energy in C_2 can be transferred to C_1 so that the voltage across C_1 is approximately two times of the peak voltage in the single series diode configuration. The breakdown voltage of the rectifier is increased hence the theoretical maximum conversion efficiency

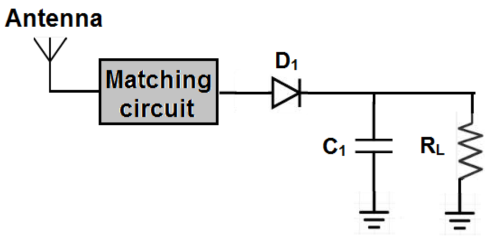

Fig. 2. Configuration of a conventional single series diode rectifying circuit.

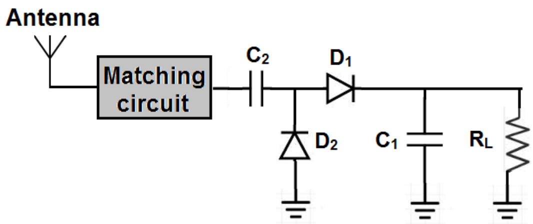

Fig. 3. Configuration of a conventional voltage doubler rectifying circuit.

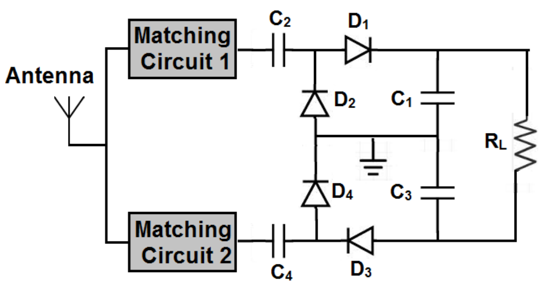

Fig. 4. Configuration of the novel full-wave Greinacher rectifying circuit with two-branch impedance matching circuit.

of the rectifier is also improved. Moreover, the biasing voltage of D_1 is provided by using part of the rectified wave from D_2, which reduces the input RF power requirement (hence to improve the power sensitivity). In order to improve the sensitivity and efficiency further, a full-wave rectifier, named Greinachar [28], is selected for our rectenna design. It is equivalent to a two-stage voltage doubler circuit formed in a bridge type and the topology is given in Fig. 4. There are two branches with 2 diodes in each branch. The biasing voltage of each diode can be partially produced by the output of the previous diode. The total RF power consumption is reduced by using the new configuration. The power sensitivity is improved and a good power handling capability is achieved by using the mechanism of full-wave rectification. A proper choice of the diode is also critical since itself could be a main source of loss and may affect the overall circuit performance. The Schottky diode SMS7630 is selected for the rectifier due to its low biasing voltage requirement for a weak input signal (forward bias voltage: 60–120 mV @ 0.1 mA) [29].

The impedance matching circuit is a crucial and also difficult part of this design. Due to the non-linearity of the rectifier, the input impedance of the rectifier varies with the frequency, input power level and load resistance. Different from the conventional rectenna design for a fixed frequency and input power level, the rectifying circuit for energy harvesting needs to match with the dynamic conditions of the ambient input signal. The impedance needs to be matched not only as a function of the frequency, but also as a function of the input power level. Thus, a novel two-branch impedance matching circuit has been designed and optimized to meet the requirement using the Advanced Design System (ADS) software. The final design is shown in Fig. 5. The upper branch consists of a radial stub, a short stub and a 6 nH chip inductor and is aimed to get the circuit matched around 1.8 GHz and 2.5 GHz. The lower branch consists of a bent short stub and a 1.8 nH chip inductor and is aimed to get the circuit matched around 2.1 GHz. The four chip capacitors are selected as 100 nF and the diodes are two pairs of Schottky diodes. A non-linear spice model with parasitic for the Schottky diode, provided by Skyworks Solutions Inc. [29], is used in the simulation. The chip capacitors and inductors are modelled using S-parameter files provided by Murata and Coilcraft. The initial design was produced for the -35 dBm input power with input impedance of 16.4 – 153.5j @ 1.8 GHz, 13.2 – 122.3 j @ 2.1 GHz and 10.7 – 90j @ 2.5 GHz. The Harmonic Balance simulation of ADS was then employed to optimize the matching network to higher input power levels (up to -10 dBm). An accurate EM tuning was also used to optimize the parameters of the matching network. As shown in Fig. 6, after the optimization, the reflection coefficient S_{11} of the rectifier for the power levels of interest is less than -6 dB over the entire frequency band and less than -10 dB for the three centre frequencies. Since the impedance matching circuit was built on two different branches, the size of the circuit was small and compact. The designed circuit was printed on a 32 × 32 mm^2 PCB board.

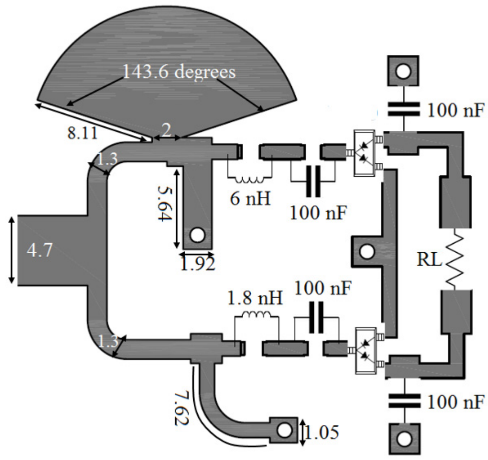

Fig. 5. Topology of the proposed rectifying circuit with a two-branch impedance matching network. The parameters are in unit: mm.

The RF to DC conversion efficiency of the rectifier can be expressed as:

$$\eta_{RF-DC} = \frac{P_{DC}}{P_{RF}} = \frac{V_{DC} \times I_{DC}}{P_{RF}} = \frac{V_{DC}^2}{P_{RF} R_L} \qquad (1)$$

where P_{DC} is the output power in DC, P_{RF} is the input RF power

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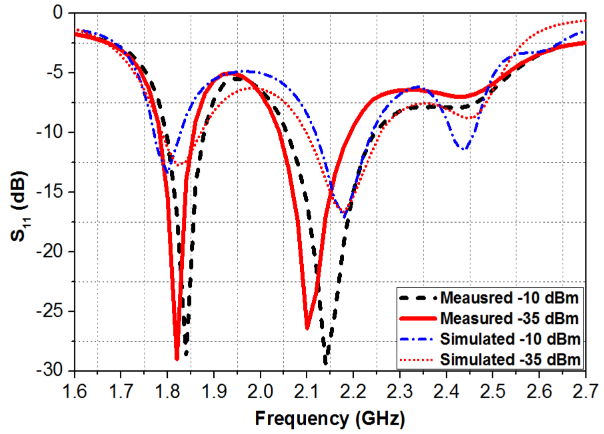


Fig. 6. Measured and simulated S_{11} of the rectifier for two power levels.

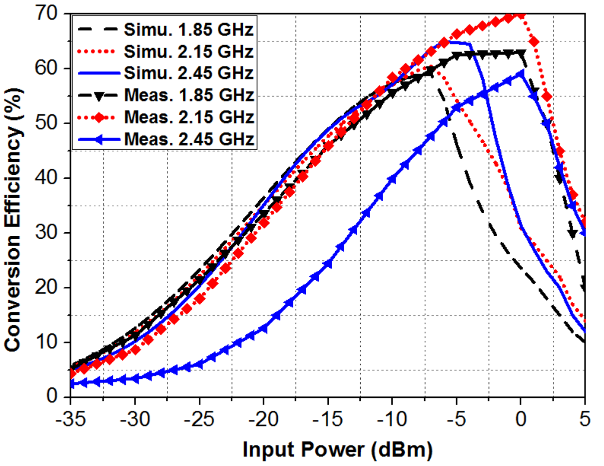


Fig. 7. Measured and simulated RF-to-DC conversion efficiency of the rectifier vs. input power at three frequencies. Load resistance: 14.7 kΩ.

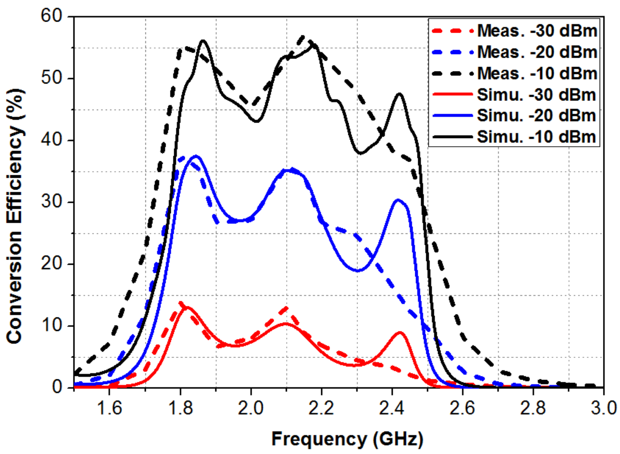
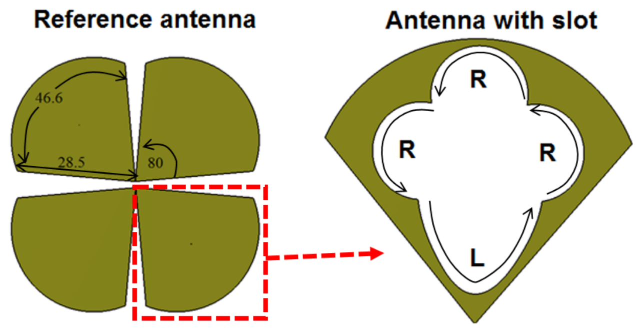
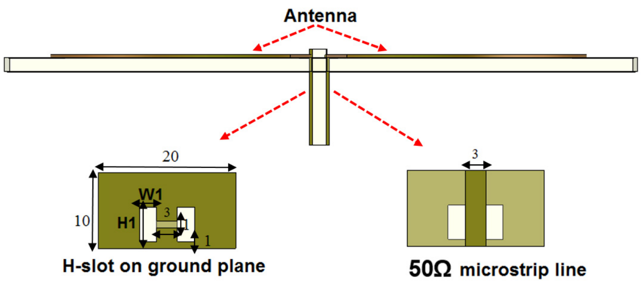


Fig. 8. Measured and simulated RF-to-DC conversion efficiency vs. frequency at three input power levels. Load resistance: 14.7 kΩ.

to the rectifier, V_{DC} is the output voltage, I_{DC} is the DC current and R_L is the load resistance. By sweeping the load resistance from 1 kΩ to 100 kΩ during the circuit optimization, the optimal load is found to be 14.7 kΩ so that the conversion efficiency is the highest. An RF signal generator was used as



(a)



(b)

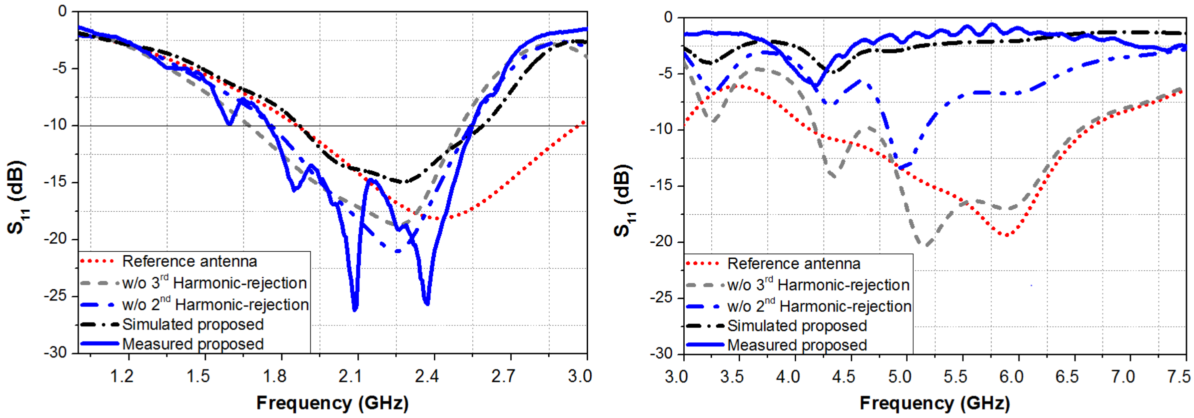
Fig. 9. A cross-dipole reference antenna is converted to an antenna-filter structure. (a) Front view. (b) Side view. R = 19.2 mm, L = 28.3 mm, W_1 = 2.5 mm, H_1 = 2.5 mm. Parameters are in unit: mm.

TABLE I
COMPARISON WITH PREVIOUS RECTIFIERS

Ref.	Operating frequency (GHz)	Bandwidth (MHz)	Measured maximum efficiency (%)	Input power level of interest (dBm)
[3]	2.45	100 (2400 – 2500)	67	-25 to -5
[31]	2.45	NA*	70	20 to 30
[32]	2.45	NA*	80	13 to 20
[7]	0.9	NA*	75	-7 to 10
[8]	1.8. 2.2	150 (1800 – 1900, 2050 – 2200)	55	-30 to -10
[33]	0.9/2.45	NA*	88/77	-10 to 20
[10]	0.915, 2.45	NA*	50	-15 to 0
This work	**1.8 – 2.5**	**700 (1800 – 2500)**	**70**	**-35 to -10**

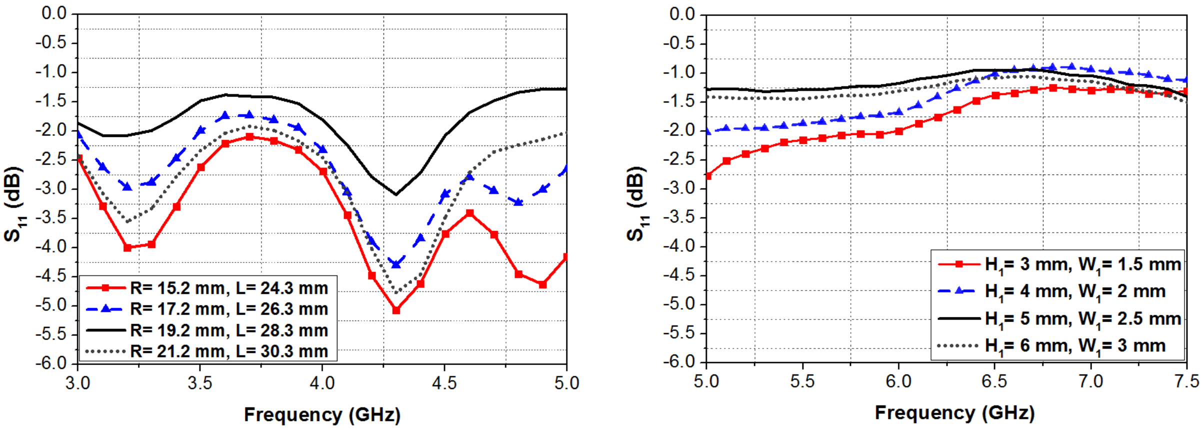
*NA: Not Available.

the source of input to the rectifier during the measurement. The measured and simulated RF to DC conversion efficiency (with the optimal load) at the three centre frequencies as a function of the input power is depicted in Fig. 7. A good agreement between the simulated and measured results has been achieved at frequencies 1.85 GHz and 2.15 GHz while the measured conversion efficiency is smaller than the simulated at 2.45 GHz – this might be due to the loss of the diodes and the PCB at



(a) (b)

Fig. 10. S_{11} of four different antennas. (a) the fundamental frequency band. (b) the higher order harmonic frequency band.



(a) (b)

Fig. 11. Simulated S_{11} with different values of (a) R and L. (b) H_1 and W_1.

higher frequencies and the unavailable parasitic behaviour of the SMD components. The conversion efficiency is increased from 5% (@ -35 dBm input) to 55% (@ -10 dBm input), which demonstrates that the proposed rectifier is with good power sensitivity and is highly efficient for the relatively low input power. The measured maximum efficiency is about 70% at 2.15 GHz when the input power to the rectifier is 0 dBm. The frequency-dependent conversion efficiency of the rectifier at three input power levels is depicted in Fig. 8. It can be seen that the conversion efficiency of the proposed rectifier over the desired frequency band (1.8 – 2.5 GHz) is greater than 40%, 20% and 5% at the input power level of -10 dBm, -20 dBm and -30 dBm respectively.

For a better evaluation, a comparison with some recent rectifier designs is given in Table I where the most important parameters such as the frequency, bandwidth, RF-DC conversion efficiency and the input power level are presented. If we consider that a broadband device should have a fractional bandwidth of 15%, our device seems to be the only one which works well over a wide bandwidth and has very high conversion efficiency when the input power level is low. It is better than the other published results in terms of the overall performance.

B. Antenna design

The antenna for wireless energy harvesting normally has special requirements because of the randomness of the ambient RF signal. A cross dipole antenna is selected due to its dual-polarization and broad beam-width which are suitable for incoming waves with arbitrary polarization and different incident angles [30]. Additionally, the harmonic-rejection property is desirable since the rectifier can produce higher order harmonic signals which may be radiated by the antenna to reduce power conversion efficiency. The bandwidth of interest is 1.8 – 2.5 GHz, thus the 2nd and 3rd harmonic frequencies are 3.6 – 5 GHz and 5.4 – 7.5 GHz respectively. The conventional approach for the harmonic rejection is to use a low/band pass filter between the antenna and the rectifier to reject the higher order harmonics. It is much more difficult to reject a broadband signal rather than a narrow-band signal. The broadband filter may increase the overall dimensions of the rectenna and the insertion loss significantly [17]. Thus a novel approach is developed to integrate the antenna and the filter structures. As shown in Fig. 9(a), the reference antenna (the starting point) consists of two pairs of planar cross dipoles. By cutting a flower-shaped slot on each sector/pole, the surface current

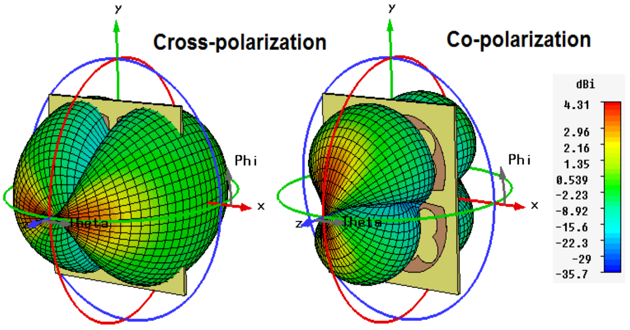


Fig. 12. Simulated 3D radiation patterns at 2.45 GHz.

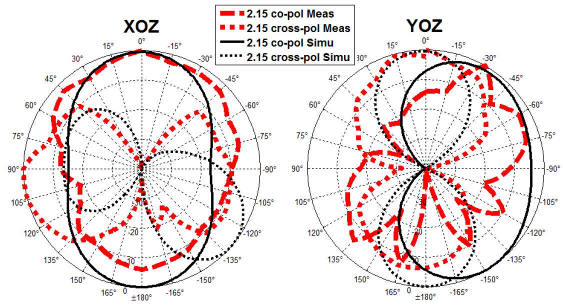


Fig. 14. Measured and simulated 2D radiation patterns at 2.15 GHz.

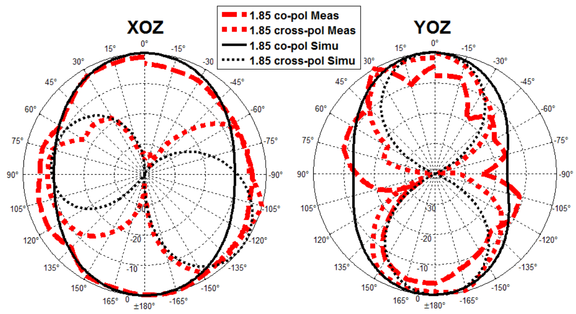


Fig. 13. Measured and simulated 2D radiation patterns at 1.85 GHz.

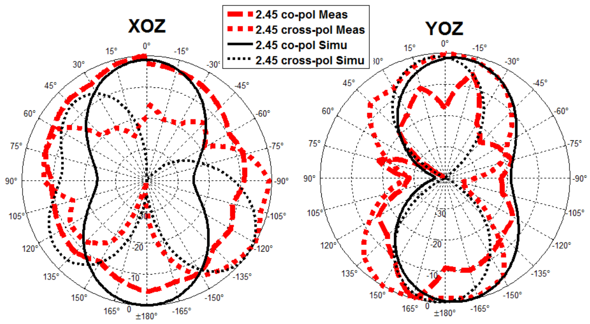


Fig. 15. Measured and simulated 2D radiation patterns at 2.45 GHz.

length can be changed. Moreover, there are three 'petals' on the slot, the impedance at the 2nd harmonic frequencies can be increased/decreased by tuning the circumference of the slot. An H-shaped slot is produced on the ground plane of the antenna micro-strip feed line which is at the back and orthogonal to the antenna, as shown in Fig. 9(b). The impedance at the 3rd order harmonic frequencies can be changed by modifying the size and position of the H-shaped slot. The antenna is optimized using the CST Microwave Studio. After optimization, the higher order harmonic signals are suppressed and the optimal parameters of the antenna are given in Fig. 9.

The simulated and measured reflection coefficients (S_{11}) are shown in Fig. 10(a) and (b). It can be seen that the reference antenna works well (S_{11} < -10 dB) over the desired frequency band 1.8 – 2.5 GHz but it also has small reflection coefficients (< - 7 dB) over the 2nd and 3rd harmonic frequencies (3.6 GHz to 7.5 GHz) which means there is very limited band rejection for the higher order harmonic frequencies. By introducing the slot on the reference antenna, the antenna impedance is mismatched at the 2nd harmonic frequency band between 3.6 GHz and 5 GHz. But the frequencies for the 3rd harmonics are not covered. By adding an H-slot on the feed line, the 3rd harmonic signals can be rejected as shown in Fig. 10(b). The measured S_{11} for the complete antenna system is greater than -1.5 dB at the most frequencies from 3.6 GHz to 7.5 GHz (except 4.2 GHz) and is less than -10 dB at the desired bandwidth from 1.8 GHz to 2.5 GHz. A good agreement between the simulated and measured S_{11} of the proposed antenna is demonstrated. It is important to reject both the 2nd and 3rd order harmonics since both of them could produce significant loss in reality.

Fig. 11(a) shows that the simulated S_{11} over the higher harmonic frequency band with different dimensions of the flower-shaped slot on the planar antenna. Increasing the values of R and L as shown in Fig. 9(a), the circumference of the slot is increased and the change of S_{11} is quite significant at 2nd harmonic frequencies. The values of S_{11} are increased from -4 dB @ 3.25 GHz, -5 dB @ 4.3 GHz and -4.5 dB @ 4.9 GHz to -2.1 dB, -3 dB and -1.25 dB respectively. When R = 19.2 mm and L = 28.3 mm, the result is the optimal since the S_{11} starts to decrease with the increase of these dimensions. The simulated reflection coefficient with different dimensions of the H-slot is depicted in Fig. 11(b). By increasing the height and width of the H-shape slot, the S_{11} is changed from a low level of -2.5 dB to a high level of -1.25 dB at the 3rd order harmonic band (from 5.4 GHz to 7.5 GHz). The optimal result is achieved with H_1 = 5 mm and W_1 = 2.5 mm.

The simulated 3D radiation pattern of the proposed antenna at 2.45 GHz is shown in Fig. 12. It can be seen that both the co-polarization and cross-polarization radiated fields of the antenna are high which means the antenna is able to receive RF waves with either vertical polarization or horizontal polarization and has demonstrated that the antenna is indeed dual polarization. Additionally, the radiation pattern is shown to be bidirectional with a broad beam-width, thus the antenna can receive incident signals from many different angles. Therefore the antenna is very suitable for wireless energy harvesting. The simulated and measured 2D patterns of the antenna at 1.85 GHz, 2.15 GHz and 2.45 GHz are shown in Figs. 13, 14 and 15 respectively. The half-power beam-width is 109° at 1.85 GHz, 95.6° at 2.15 GHz and 87.5° at 2.45 GHz. The

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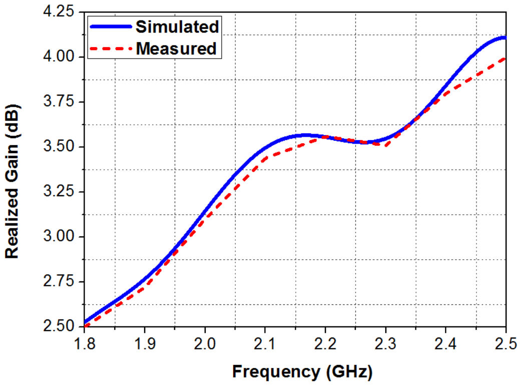

Fig. 16. Simulated and measured realized gains versus frequency

simulated and measured realized gains of the antenna are plotted in Fig. 16.

III. Rectenna Measurement and Comparison

Having optimized both the antenna and the rectifier, the rectenna was made. The measurement of the proposed rectenna was conducted in two phases.

1) Using a known power source: A broadband antenna was connected to an RF signal generator to transmit signals from 1 GHz to 3 GHz with a step size of 50 MHz. A power amplifier with a maximum gain of 30 dB was used so that the maximum available transmit power was up to 43 dBm. A fabricated prototype antenna was first used to receive the signals at various power levels at a distance of 1 m (in the antenna far field). The received RF power was measured using a spectrum analyzer and the corresponding transmitting power was recorded. The antenna was then replaced by the rectenna at the same location. The output DC voltage across the load was obtained. The corresponding received power was tunable from -35 dBm to 0 dBm by changing the transmitting power. The output DC power in dBm can be calculated by:

$$P_{DC}\,(dBm) = 10 \times \log_{10}\left(\frac{V_{DC}^{2}}{R_L} \times 10^{3}\right) \qquad (2)$$

where V_{DC} is the measured output voltage and R_L is the optimal load (14.7 kΩ). The measured output DC power and conversion efficiency of the rectenna as a function of the received RF power and frequency are depicted in Fig. 17(a) and (b). From 1.8 GHz to 2.5 GHz, the measured highest DC power was about -12.6 dBm when the RF power received by the antenna was -10 dBm. The corresponding conversion efficiency was 54.9%. When the received power was as low as -35 dBm, the highest DC power was found to be -46.8 dBm with a conversion efficiency of 6.6%. The maximum measured conversion efficiency was found to be 70% when the received power was 0 dBm.

2) With an ambient power source: To evaluate the performance of the new broadband rectenna in reality, we selected a typical indoor office environment with a relatively low ambient RF power density to conduct the measurement.

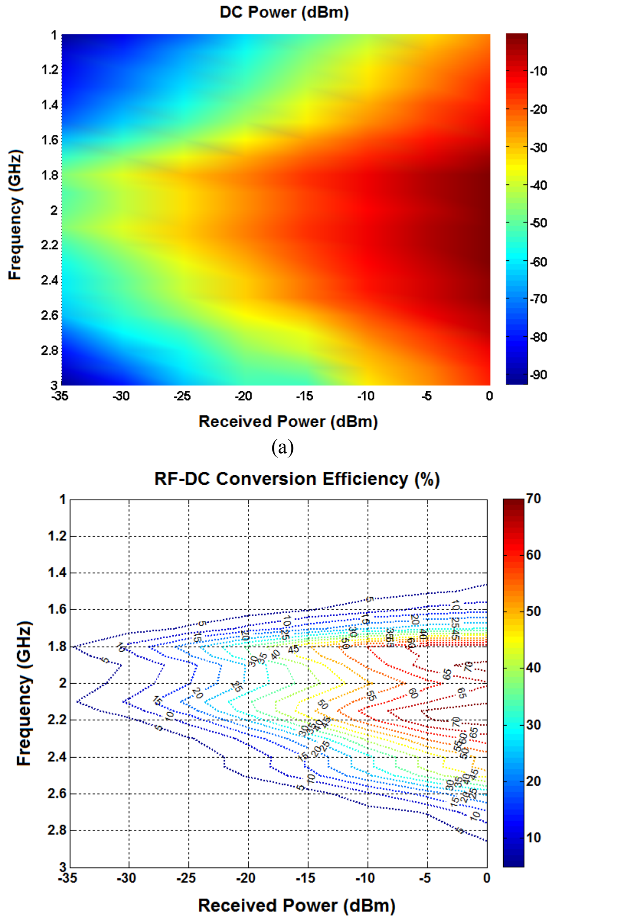

Fig. 17. (a) Measured output DC power of the rectenna as a function of the received RF power and frequency. (b) Measured conversion efficiency of the rectenna

Firstly, we used the proposed antenna and a spectrum analyzer to measure the amount of the received power. The typical received power in dBm as a function of frequency is depicted in Fig. 18. It can be seen that the power is mainly distributed at three frequency bands which are GSM-1800/4G, UMTS-2100/3G and Wi-Fi. The input power level over the entire band is around -37 – -32 dBm. The total power in the band of interest was measured by using a wideband power sensor provided by Rothde & Schwarz [34], as shown in Fig. 19. The measured total power in the band received by antenna was varying between -20 dBm and -12 dBm as a function of time. The average total power in the band was around -14.3 dBm. Secondly, the antenna was replaced by the rectenna and the output voltage was measured using a voltage meter, as shown in Fig. 20. The measured output voltage was around 250 – 300 mV. Using equation (2), the DC power was found to be -23.7 – -22.1 dBm which seems to be higher than the incident power levels of -37 to –32 dBm. This is because our rectenna is of a broad bandwidth and has combined received power over its band into DC power, the summation (the total power) is therefore larger than the input power at a specific frequency. If the average total received power in the band is divided by the

TABLE II
COMPARISON OF THE PROPOSED RECTENNA AND RELATED DESIGNS

Ref.	Frequency (GHz)	Dimension (mm^3)	Maximum conversion efficiency (%) @ -10 dBm input	Measured maximum conversion efficiency (%)	Received wave type	Measured DC power @ ambient input power level (dBm)
[1]	Single-band 2.45	80×87×0.635	70	70	CW*	Meas. -40 @ -30
[8]	Dual-band 1.8, 2.2	300×380×1.6	50	50	MW*	Meas. -24.5 @ -30
[9]	Multi-band 0.9 , 1.75 2.15, 2.45	155×155×7.2	16	60	CW*	NA*
[10]	Dual-band 0.915, 2.45	60×60×60	35	50	CW*	NA*
[11]	Dual-band 0.915, 2.45	61.5×48×0.025	56.2	56.2	CW*	NA*
This work	**Broad-band 1.8 – 2.5**	**70×70×13.2**	**55**	**70**	**MW***	**Meas. -19.7 @ -30**

*CW: Continuous Wave.
*MW: Modulated Wave.
*NA: Not Available

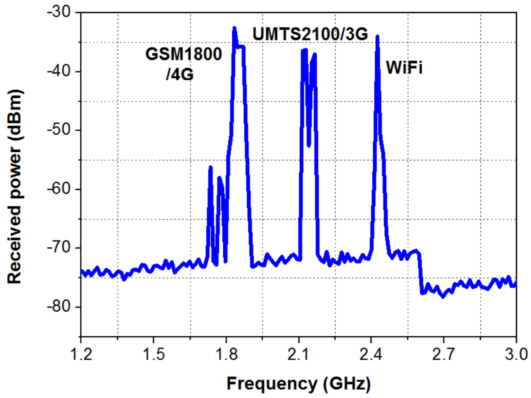

Fig. 18. Measured received power of the antenna in reality in an office.

Fig. 20. Rectenna measurement in a typical indoor ambience with a voltage meter

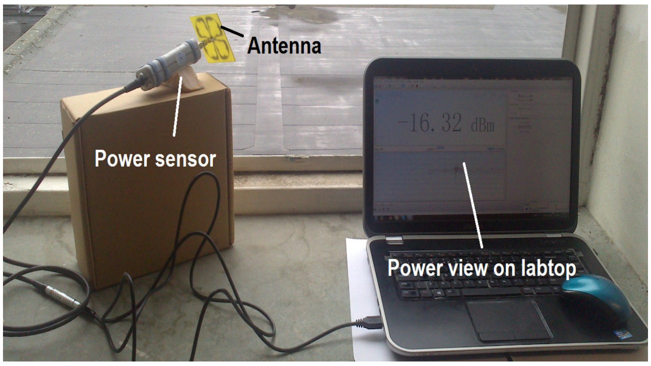

Fig. 19. Total power in the band measured by using a wideband power sensor.

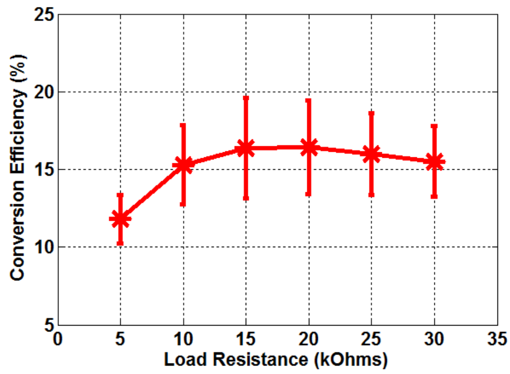

Fig. 21. Measured overall conversion efficiency versus different load with error bar

output DC power, the overall power conversion efficiency in this scenario was around 16.6%. In the same condition, the rectenna was also measured in multiple times by changing the load resistor. The measured overall conversion efficiency versus different load from 5 kΩ to 30 kΩ is depicted in Fig. 21 with an error bar. The variability of the result was due to the difference of the measured DC power. It can be seen that the highest overall conversion efficiency was achieved with the optimal load of around 15 kΩ.

A comparison between our rectenna design and some related designs is given in Table II. It can be seen that the majority of the previous work is for single-band, dual-band or multi-band operation. This work provides a broadband design with a higher conversion efficiency. The dimension of our design is smaller than most of the previous designs in term of the volume. If we assume all these rectennas were placed at the same place with the same ambient low input power level at each frequency band, say -30 dBm, the expected measured output DC power levels are given in the last column, it is evident that our design has produced the highest DC output power due to its high conversion efficiency and wide frequency bandwidth. Most of the published designs are not able to produce sufficient output DC power at such a low ambient power level.

IV. Conclusion

A high-efficient broadband rectenna has been proposed for ambient wireless energy harvesting. A novel broadband rectifying circuit with a new impedance matching circuit has been designed to match with the ambient RF signals with a relatively low power density. The power sensitivity has been improved by using a full-wave rectifier circuit configuration. A broadband dual-polarization cross dipole antenna has been designed to enhance the antenna receiving capability. The harmonic rejection property has been embedded in an integrated antenna by using a novel slot-cutting approach in order to improve the overall efficiency and keep the overall size as small as possible. The simulated and measured results have shown that the rectenna has maximum conversion efficiency of around 55% for -10 dBm input power from 1.8 GHz to 2.5 GHz. The power sensitivity is down to -35 dBm. The rectified DC power can be well above the incident power from any single resource due to the broadband operation and high efficient design. Considering the high DC power output of this design in a relatively low power density environment, this rectenna can be used for efficient wireless energy harvesting for a range of wireless sensor and network applications.

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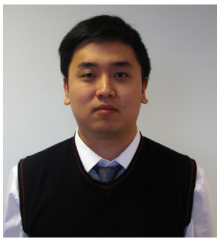

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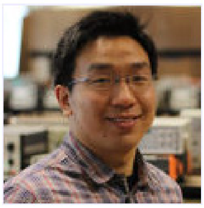

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