A Novel Compact and Frequency-Tunable Rectenna for Wireless Energy Harvesting

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***Abstract*— This paper presents a novel rectenna with a wide tunable operating frequency band without introducing a complex impedance matching network. It shows significant advantages over the existing rectennas in terms of the structure and cost. A rectenna example has been designed with a compact size of 90 × 90 × 1.58 mm^3 and operates at four different frequency bands from 1.1 to 2.8 GHz. Over 60% energy conversion efficiency is achieved for the desired frequency band. The proposed rectenna shows good performance for the wireless power transfer and wireless energy harvesting applications with a much-simplified structure and reduced cost.**

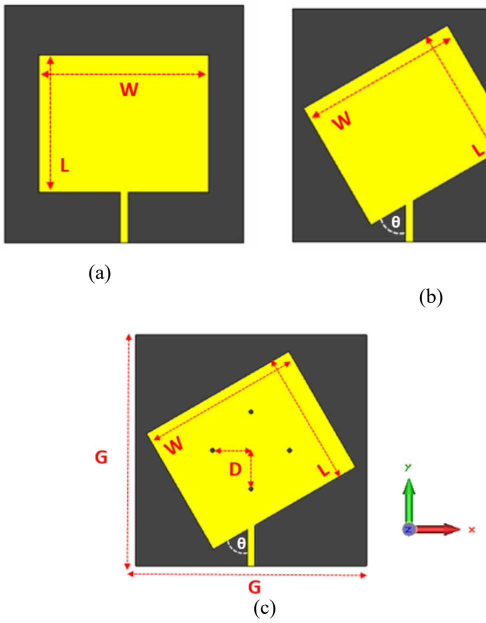
Keywords—broadband rectenna; frequency-tunable; wireless energy harvesting;

I. INTRODUCTION

Wireless power transfer (WPT) and wireless energy harvesting (WEH) using rectennas are becoming an emerging technology. Therefore, much progress on rectennas for WPT and WEH has been made [1]-[6]. Among them, multiband and broadband rectennas with good/excellent performance (e.g., high conversion efficiency and improved linearity) have shown significant advantages over other types of rectennas in terms of the total output power and suitability for different operating conditions. However, the optimal design of such rectennas is still challenging due to the nonlinearity of the system. So far, there have been very few multiband and broadband rectennas reported with excellent performance [4]-[6].

In addition, the aforementioned conventional rectennas normally use antennas matched to standard 50 Ω. The matching networks should match the complex high impedance of the rectifiers to 50 Ω as well. In this scenario, the performance of the rectenna would be very sensitive to the impedance variation of the rectifier [3]. Thus it is difficult to achieve consistent conversion efficiency in different operating conditions due to the impedance variation and mismatch.

In this paper, we introduce a novel design method for a frequency tunable rectenna. An important feature is that the proposed rectenna does not require the additional matching networks, which is very different from existing rectennas. The antenna impedance is directly (complex conjugate) matched with the rectifier impedance at several desired frequency bands. Thus the proposed rectenna is of a relatively simple structure, a compact size and low cost. In addition, the frequency bands of interest can be easily tuned by loading a number of shorting pins on the antenna. Moreover, this novel design concept generates a high impedance complex conjugate matching system that could significantly reduce the nonlinear effect of the rectenna. The proposed rectenna is therefore adaptive for a wide input power range and load impedance range. The detailed design steps are introduced in the following sections.



(a)

(b)

(c)

Fig. 1. (a) A typical center-fed patch (CFP) antenna. (b) An off-center-fed patch (OCFP) antenna. (c) The proposed off-center-fed patch with shorting pins.

II. COMPACT FREQUENCY TUNABLE RECTENNA DESIGN

A. Antenna Desgin

The antenna for this design is a special type of high impedance antenna where its impedance can directly (complex conjugate) match with that of the rectifier. Here, we have proposed a new method to manipulate the input impedance of a typical microstrip patch antenna. The antenna can therefore be tuned to match with the rectifier at the desired wide frequency band, and mismatch at other frequencies (for harmonic rejection). Using this method, we could get rid of the complex matching network of the conventional multiband/broadband rectennas, but the proposed rectenna could still achieve competitive performance for the target applications (WPT and WEH).

The microstrip patch is one of the most common antennas. It has attractive features such as low cost, simple to design and easy to fabricate. As a design example, we employ a patch antenna using Rogers Duroid5880 substrate with a relative permittivity of 2.2 and a thickness of 1.58 mm. As shown in Fig. 1(a), the copper patch on the top layer has a thickness of 70 µm and a size of $W \times L$ mm^2. The patch is fed by a microstrip line. The size of the PCB is $G \times G$ mm^2. From the theory [7], if $W = 64$ mm, $L = 56$ mm and $G = 90$ mm, the fundamental resonant frequency of the patch antenna is therefore estimated as 1.84 GHz. The antenna performance is also validated by using software simulations with the aid of the CST software. As shown in Fig. 2, the simulated real part (resistance) and imaginary part (reactance) of the antenna impedance show that the resonant frequency of the patch is of around 1.85 GHz (for resistance = 50 Ω and reactance = 0 Ω) which verifies the predictions. Additionally, the antenna also has anti-resonant performance at about 1.8 GHz, since the resistance is relatively high (e.g., about 200 Ω) while the reactance varies rapidly from 150 to -50 Ω at 1.8 GHz. In our case, the anti-resonant high impedance of the antenna would be used to directly match with the impedance of the rectifier. However, it is well known that the conventional microstrip center-fed-patch (CFP) antenna is always of a narrow frequency bandwidth. The frequency ratio of the CFP is normally larger than 2. Consequently, if such CFPs are used for rectenna design without a matching network, the rectenna is only possible for a single narrow operating frequency band.

To adjust the frequency ratio of the CFP, we introduce a novel feeding method. As shown in Fig. 2(b), based on the shape center of the patch, the antenna is rotated anti-clockwise by $90 - \theta$ degrees. Thus the pitch angle between the patch and the feed line is θ ($\theta = 60^{\circ}$). In this case, the antenna is an off-center-fed patch (OCFP). Due to this unbalanced feeding structure, multiple resonant frequencies are created between the fundamental and second resonant frequencies of the antenna, which has been demonstrated in our previous work [6]. From Fig. 3, it can be seen that the OCFP has realized three anti-resonant frequencies with relatively high impedance at around 1.5, 1.8 and 2.4 GHz respectively. Compared with the conventional CFP, the frequency ratio of the antenna is changed from 1: 2 to about 1: 1.2.

Next, two pairs of identical shorting pins are symmetrically loaded on the OCFP with the aim to achieve tunable flexible impedance matching for the rectenna design. The shorting pins are conducting holes which are electrically connected to the ground plane of the PCB. As depicted in Fig. 2(c), each hole has a diameter of 0.8 mm and a distance of D to the center of the PCB. The value of D in this figure is 15 mm as an example. As shown in Fig. 3, the proposed OCFP with shorting pins has created an additional anti-resonant frequency band around 2.15 GHz with high impedance value of around 200 + j 150 Ω. In order to achieve a tunable operating frequency band for the proposed rectenna, the positions of the shorting pins can be tuned. According to the theory [8], when the distance between the pins and the center of the patch is changed, the current strength on the edges and center areas of the patch is varying.

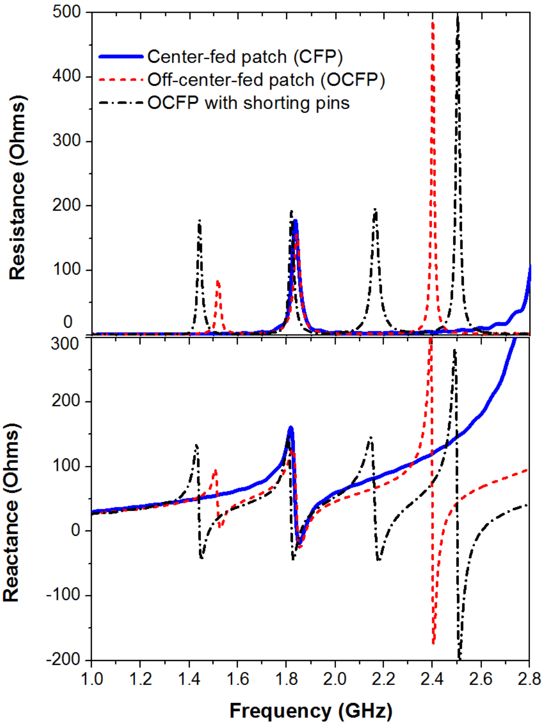


Fig. 2. The simulated real part (resistance) and imaginary part (reactance) of the impedance of the center-fed patch (CFP) antenna, off-center-fed patch (OCFP) antenna, and the proposed OCFP with shorting pins.

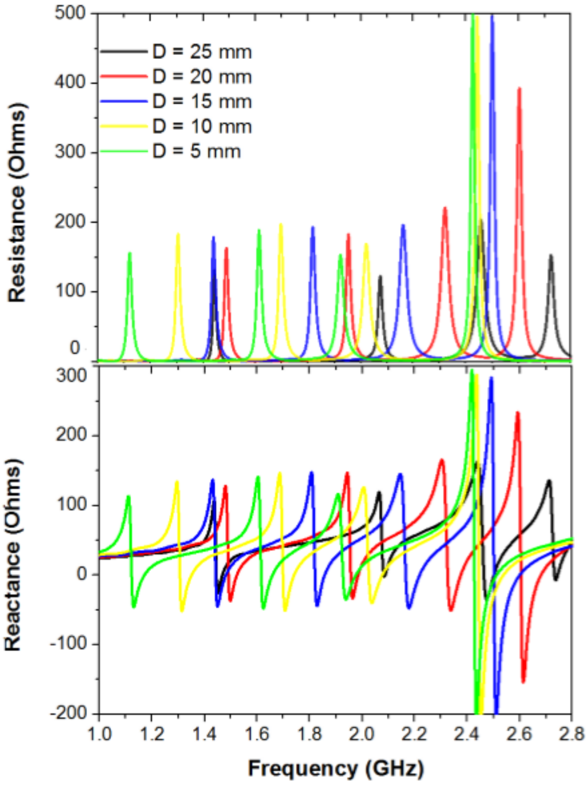


Fig. 3. The simulated real part (resistance) and imaginary part (reactance) of the proposed antenna with different values of parameter D.

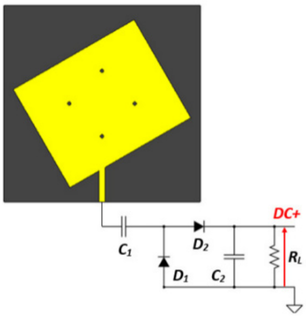


Fig. 4. The rectenna design using the proposed OCFP with shorting pins. The capacitors *C1* = *C2* = 100 nF, diodes *D1* and *D2* are HSMS2852, and *RL* = 2000 Ω.

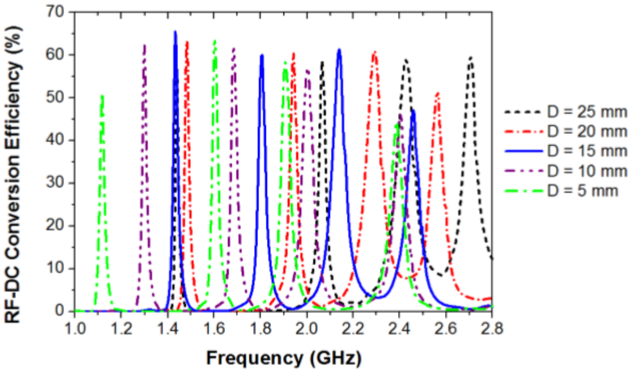


Fig. 5. The simulated RF-DC conversion efficiency of the proposed rectenna with different values of *D*. The received power by the rectenna is 0 dBm.

As an example, we have studied the effects on the resonant frequency bands of the antenna by changing the value of *D*. The simulated resistance and reactance of the proposed antenna are shown in Fig. 3. It can be seen that the four resonant and anti-resonant frequency bands of the antenna are tunable from 1 to 2.8 GHz when the value of *D* is changed between 5 to 25 mm. Without modifying the physical dimension of the patch, the electrical size of the antenna is therefore tunable from 0.28 λ_0 to 0.78 λ_0 by changing the positions of the shorting pins.

It is shown that, by modifying the conventional CFP to the proposed novel OCFP with shorting pins, the number of resonant/anti-resonant frequencies over the desired frequency band (with a frequency ratio < 2) is increased from 1 to 4. Multiband frequency-tunable rectenna could therefore be designed using the proposed antenna without the need of matching networks.

B. Rectifier Configuration

The schematic view of the complete rectenna using the proposed OCFP with shorting pins is shown in Fig. 4. A typical voltage doubler rectifier is selected due to its high conversion efficiency and simple topology [5]. The capacitors are typical 100 nF chip capacitors from Murata, the rectifying diodes are Schottky diode HSMS2852 from Avago and a typical 2000 Ω resistor is used as the load. The rectifier is directly connected to the antenna port without the introduction of any additional matching circuit components. The performance of the rectenna is co-simulated using the ADS and CST software. More specifically, a frequency domain power source is employed for the rectifier simulation, where the port impedance is directly linked to the antenna impedance exported from the CST.

III. RECTENNA PERFROMANCE

Fig. 5 shows an example of simulated RF-DC conversion efficiency of the complete rectenna with different locations of the pins (parameter *D*). The efficiency is calculated by $Eff._{(RF\text{-}DC)} = P_{OUT}/P_{IN}$ where P_{OUT} is the output DC power and P_{IN} is the received RF power by the antenna. It can be seen that, when the input power is 1 mW (0 dBm), the rectenna is of high conversion efficiency (about 60%) at four different frequency bands. The frequency bands of the rectenna are tunable from 1.1 to 2.7 GHz for different locations of the pins. It demonstrates that the proposed rectenna has tunable operating frequency over a broad band and also of high efficiency, the matching network of the rectenna is indeed removed that could reduce the loss, cost and avoid fabrication errors (for a complex design).

IV. CONCLUSION

A novel design method for a frequency-tunable rectenna has been presented. The proposed rectenna has achieved high conversion efficiency over a wide tunable frequency band from 1.1 to 2.8 GHz. The most important feature was that the proposed design does not require the introduction of complex impedance matching networks, thus the rectenna was of a compact size, simple structure and low cost. Compared with other design methods for broadband rectennas with similar performance, the proposed new method was of great significance for developing rectennas for the target WPT and WEH applications due to its much-reduced complexity.

REFERENCES

[1] A. Costanzo et al., “Electromagnetic energy harvesting and wireless power transmission: A unified approach,” *Proc. IEEE*, vol. 102, no. 11, pp. 1692–1711, Nov. 2014.

[2] Y. Huang, N. Shinohara, and T. Mitani, “A constant efficiency of rectifying circuit in an extremely wide load range,” *IEEE Trans. Microw. Theory Tech.*, vol. 62, no. 4, pp. 986–993, Apr. 2014.

[3] K. Niotaki, A. Georgiadis, A. Collado, and J. S. Vardakas, “Dual-band resistance compression networks for improved rectifier performance,” *IEEE Trans. Microw. Theory Tech.*, vol. 62, no. 12, pp. 3512–3521, Nov. 2015.

[4] C. Song, Y. Huang, et al, “A high-efficiency broadband rectenna for ambient wireless energy harvesting,” *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3486–3495, May 2015.

[5] C. Song, Y. Huang et al, “A novel six-band dual CP rectenna using improved impedance matching technique for ambient RF energy harvesting,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 3160–3171, Jul. 2016.

[6] C. Song, Y. Huang et al, “Matching network elimination in broadband rectennas for high-efficiency wireless power transfer and energy harvesting,” *IEEE Trans. Ind. Electro.*, *in press*, Dec. 2016. DOI: 10.1109/TIE.2016.2645505.

[7] Y. Huang and K. Boyle, *Antennas: From Theory to Practice*. Hoboken, NJ: Wiley, 2008.

[8] X. Zhang and L. Zhu, “Patch antennas with loading of a pair of shorting pins towards flexible impedance matching and low cross polarization,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 4, pp. 1226–1233, Apr. 2016.