Hindawi Publishing Corporation
International Journal of Antennas and Propagation
Volume 2014, Article ID 298127, 9 pages
http://dx.doi.org/10.1155/2014/298127

Research Article

Design of a Compact Planar Rectenna for Wireless Power Transfer in the ISM Band

Fang Zhang,[1,2] Xin Liu,[3] Fan-Yi Meng,[2] Qun Wu,[2] Jong-Chul Lee,[4] Jin-Feng Xu,[4] Cong Wang,[4] and Nam-Young Kim[4]

[1] *Bohai University, 19, Keji Road, New Songshan District, Jinzhou 121013, China*
[2] *Harbin Institute of Technology, 92 West Dazhi Street, Nangang District, Harbin 150001, China*
[3] *Harbin Institute of Technology, No. 73 Huanghe Road Nangang District, Harbin 150090, China*
[4] *Kwangwoon University, 447-1 Wolgye-dong, Nowon-ku, Seoul 139-701, Republic of Korea*

Correspondence should be addressed to Fang Zhang; fang_zhang@hit.edu.cn

Received 18 September 2013; Revised 31 December 2013; Accepted 5 January 2014; Published 20 February 2014

Academic Editor: Miguel Ferrando

This paper presents a compact planar rectenna with high conversion efficiency in the ISM band. The proposed rectenna is developed by the decomposing of a planar rectenna topology into two functional parts and then recombining the two parts into a new topology to make the rectenna size reduction. The operation mechanism of the antenna and rectifying circuit in the proposed novel topology is explained and the design methodology is presented in detail. The proposed topology not only reduces the rectenna design cycle time but also leads to easy realization at the required frequency ranges with a very low cost. For validation, a 2.45 GHz rectenna system is designed and measured to show their microwave performances.

1. Introduction

Wireless energy transfer as one of the technologies for changing the way of supplying energy has gained great attention in recent years [1–3]. As a key component in a wireless energy transmission system, the rectenna undertakes the main task to convert the received RF power into dc power which can then be consumed by other parts of the system [4–7]. In modern wireless communication systems, compact size, low cost, and high integration have always been required. Rectenna in the wireless energy harvesting faces the same challenges. In this study, we focused on a compact planar rectenna design in the ISM (Industrial, Scientific, and Medical) band at 2.45 GHz.

The rectenna design basically consists of three elements: antenna, matching network, and rectifying circuit. From the architecture's point of view, the selection of antenna has a great effect on the size and the order of the system's complexity. Patch antenna with a probe feed often causes a multilayer architecture [8]. The rectifying circuit and patch antenna share a common ground and are located on the different layers. This architecture reduces the coupling between the antenna and rectifying circuit to some extent. Patch antenna fed with a microstrip line often causes single layer architecture [9]. The patch and rectifying circuit are located in the same plane. The larger size is often needed compared with the multilayer patch antenna architecture. Coupling between the antenna and rectifying circuit also should be considered in the design. The planar dipole, loop, and bow-tie antenna often reach single plane architecture [10–12]. The filter, matching network, and rectifying circuit usually are realized by the coplanar strip line. This architecture often leads to a very low system cost. Using the harmonic rejection antenna in the rectenna for saving a filter part has been reported [11, 12]. In this way, the insertion loss introduced by the filter can be eliminated and higher system efficiency can be expected.

From the published literature, we see that a large amount of research has been done to change the type of antenna or use different filters or diodes in the rectifying part. It is worth

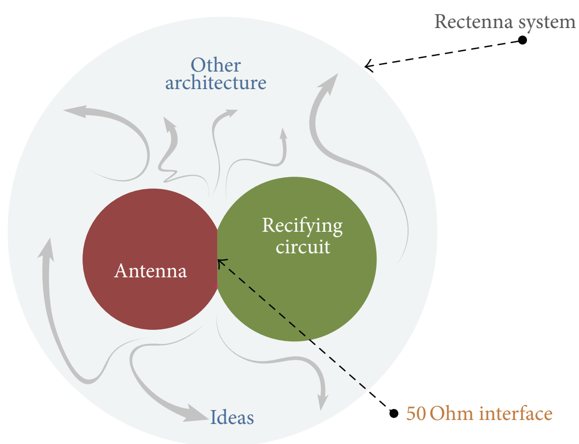


Figure 1: Aggregating relationship of 50 Ohm interface rectenna system.

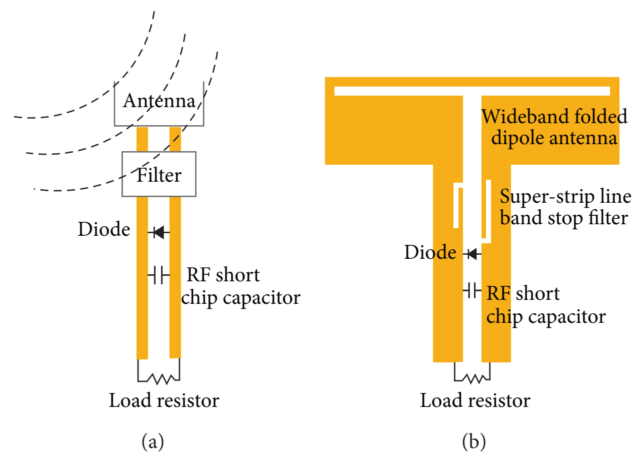


Figure 2: Schematic of the folded dipole rectenna.

pointing out that most of the rectenna designs are based on the 50 Ohm interface for reducing the total rectenna system design difficulty. The total rectenna system is designed part by part and combined through the 50 Ohm interface.

2. Rectenna Design

2.1. 50 Ohm Interface. As previously mentioned, most of the rectenna [4, 5, 7, 9] designs are based on the 50 Ohm interface. In the 50 Ohm interface rectenna system, a rectenna has already been separated into two or several parts, such as antenna part, rectifying circuit part, and other matching circuit parts. It is plain to see that the more parts the system uses, the higher the possibility of making the system a larger size and a greater power loss. In other words, theoretically, if the 50 Ohm interface rule is not used, a rectenna still can be considered a complete unit. It also opens the possibility of obtaining a highly integrated rectenna system with a more compact size, low power consumption, and higher conversion efficiency.

A more clear aggregating relationship of 50 Ohm interface rectenna system is plotted in Figure 1. From Figure 1, if the outer largest circle represents the total rectenna system design possibility, we can easily see that the rectenna using 50 Ohm interface is only part of total possibility.

2.2. Novel Topology for Compact Rectenna. This section will discuss the proposed topology of rectenna and its operating mechanism. A basic coplanar strip line (CPS) based rectenna is shown in Figure 2(a), and a realistic rectenna is shown in Figure 2(b). A wideband folded dipole antenna [13] works as a receiving antenna. A pair of super-strip lines works as a band stop filter to stop the harmonic signal generated from the diode reaching the antenna for a second radiation.

From a system's point of view, a rectenna system includes two main functional parts. One is the part for receiving RF energy, and the other is the part for rectifying it to DC. The diode is connected with these two parts in the conventional CPS based rectenna as shown in Figure 2(b). We divided it into two parts as shown in Figure 3. The principle behind such division is functionality. As shown in Figure 3 the main function of the receiving RF energy part including antenna, filter, and diode is receiving input RF energy and delivering that energy to the diode for rectifying. The main function of the rectifying part including diode, RF short capacitor, and load resistor is delivering the DC to the load and reflecting the harmonic signal back to the diode for re-rectifying to DC. Since the diode acts as a bridge connecting the antenna and rectifying circuit, we draw it in each part as shown in Figure 3. To reach a small size of the rectenna system, a novel combination method is presented which is shown in Figure 4. The system working mechanism will be explained below.

When the input RF energy transfers to the rectenna, the antenna part in the system will work to receive the energy and deliver the RF energy to the diode to be rectified. As shown in Figure 5 an RF short chip capacitor is introduced which makes the rectenna works just like a folded dipole antenna when it receives the RF energy. The upper coplanar strip line and load resistor are transparent for the RF signal. Benefiting from the large impedance tuning ability of the wideband folded dipole, the diode can be directly matched with the antenna. In this way, the received RF energy can be directly rectified by the diode. To stop the antenna from reradiating the harmonic signal generated from the diode a pair of super-strip lines is embedded in the antenna. After rectifying the received RF signal by the diode the DC power is delivered to the load resistor in the following manner. As shown in Figure 6, the RF short chip capacitor prohibits the DC power from passing through it. Thus the rectified DC power has only one path to flow which will transfer the DC power to the load resistor. The proposed rectenna works as a novel rectifying circuit. In conventional uniplanar rectenna architecture, there is a quarter wavelength coplanar strip line between the diode and RF short chip capacitor to prevent the fundamental and harmonic signals from passing to the load resistor as shown in Figure 6. In the proposed rectenna, the RF short capacitor has the same function to reject the harmonic signal and send it back to the diode for rerectifying. In this situation, the antenna and the super-strip line for

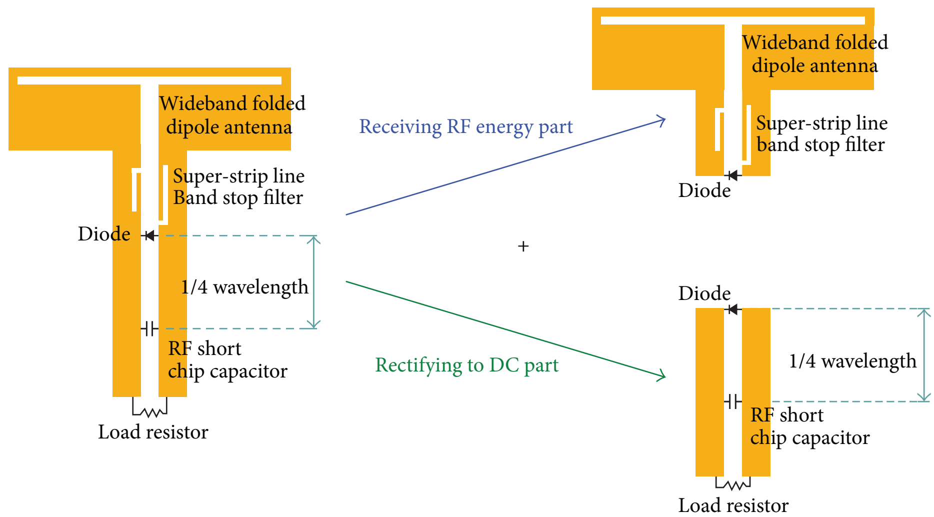


Figure 3: Schematic of decomposition of CPS based rectenna.

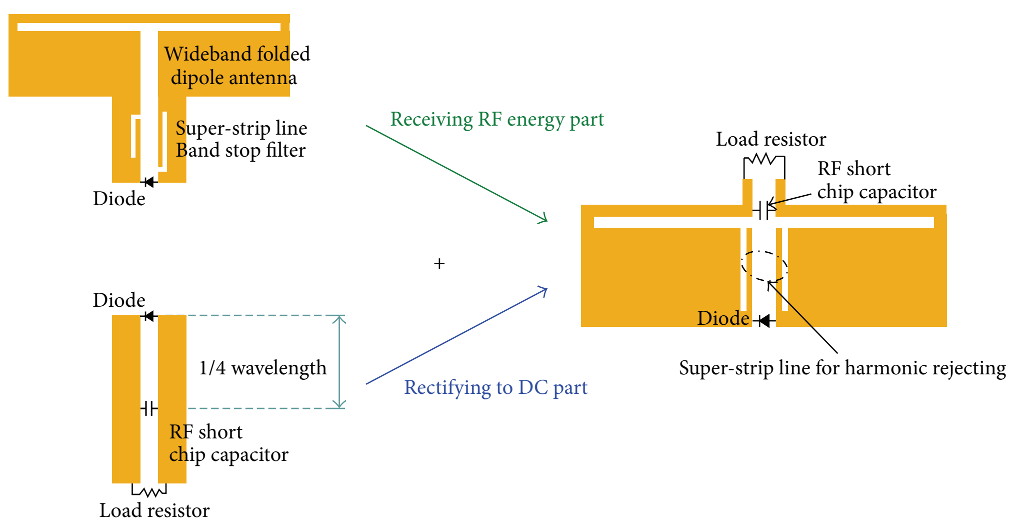


Figure 4: Schematic of combination to a novel compact topology rectenna.

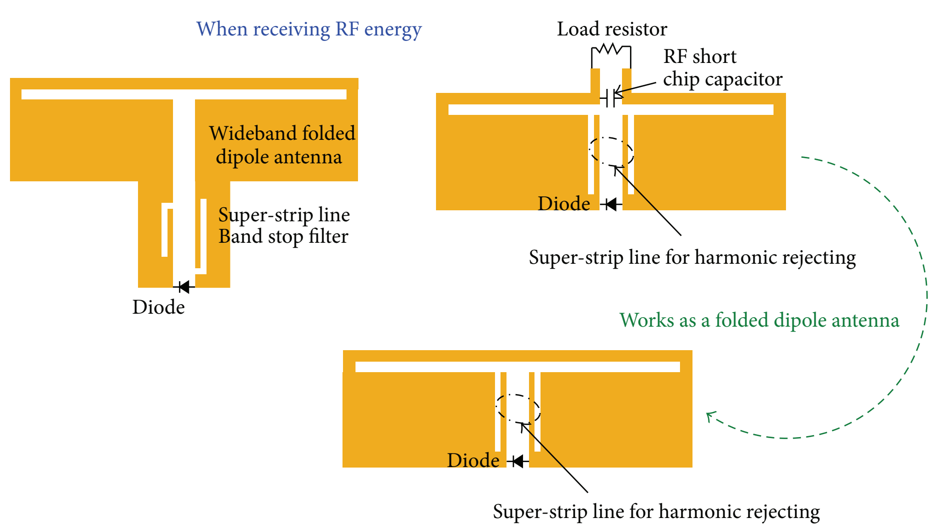


Figure 5: Schematic of proposed novel compact rectenna working to receive the RF energy.

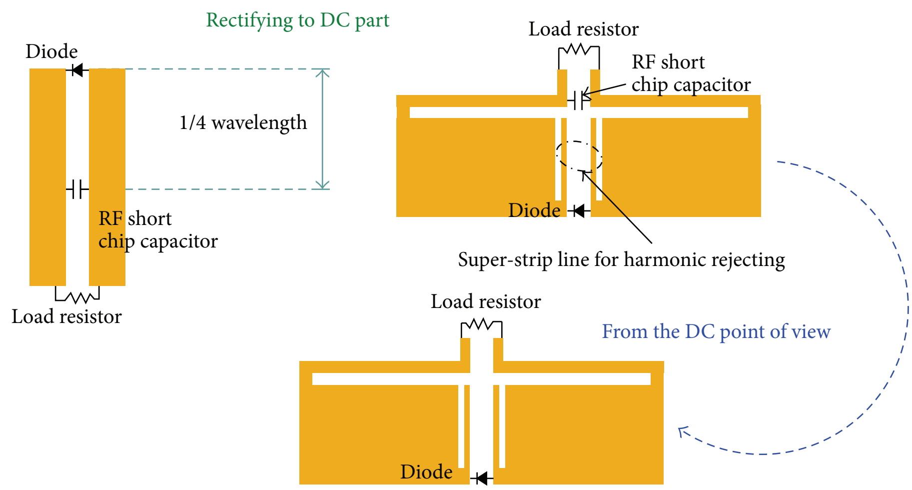


FIGURE 6: Schematic of proposed highly integrated rectenna working to deliver the DC power to the load resistor.

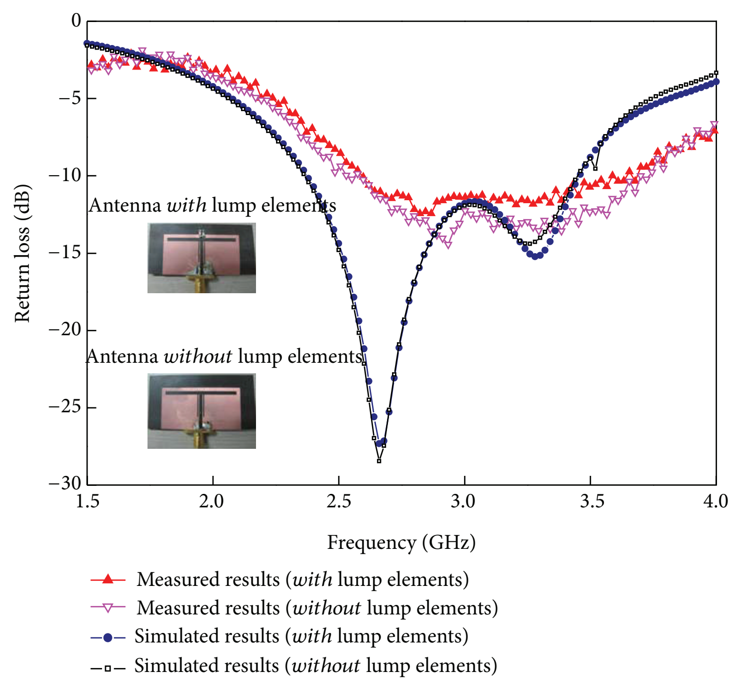
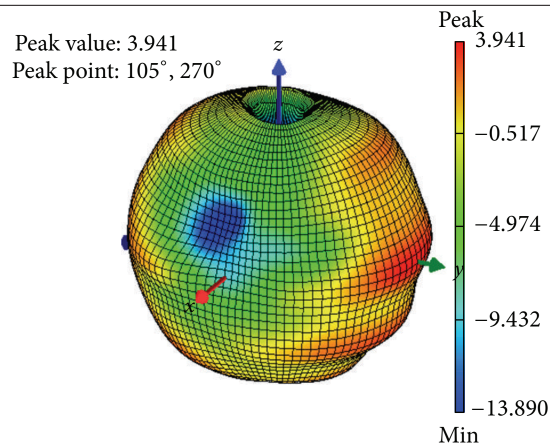
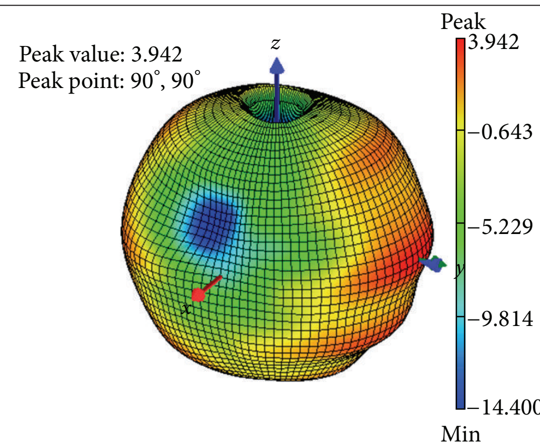
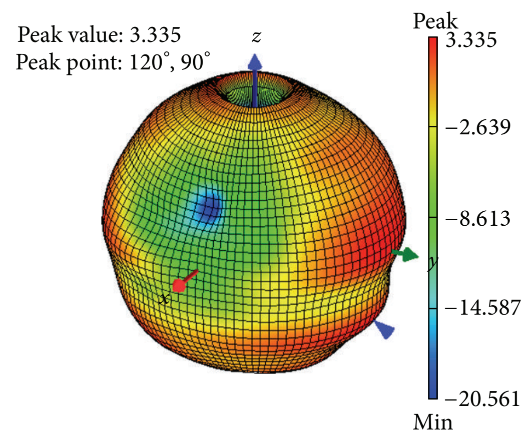
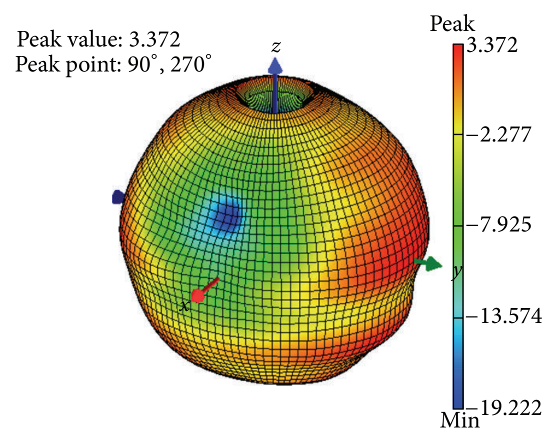
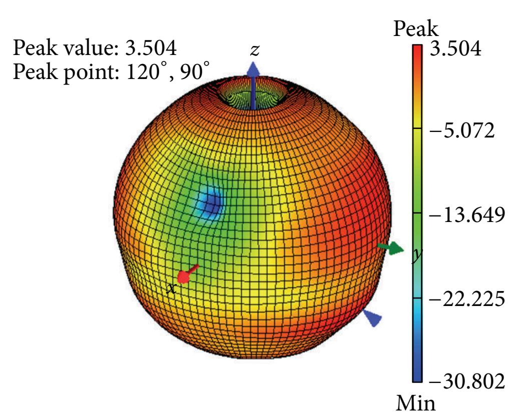
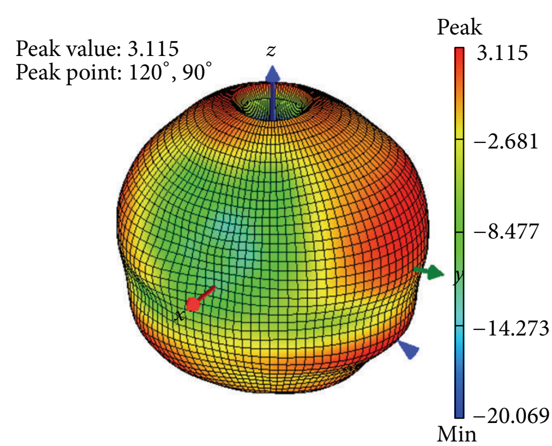


FIGURE 7: Return losses of antennas with and without lump elements.

harmonic rejecting also work just the same way as they do for receiving RF energy.

2.3. Antenna with and without Lump Elements. The proposed novel topology rectenna embeds the rectifying circuit into the antenna. The efficiency of the antenna should not be influenced greatly by the embedded lump elements including capacitor and resistor for guaranteeing the performance of the proposed rectenna. For guaranteeing the performance of the antenna, two antennas were designed and fabricated. One was embedded with lump elements and the other was not. This was the only difference between these two antennas. For simple measurement consideration, the antenna port impedance is designed as 50 Ohm. Without loss of generality, the antennas are based on the proposed topology but not on the frequency optimization. The realized operation frequency is 2.7 GHz in the simulation based on a 0.5 mm thick Teflon substrate with dielectric constant of 2.55. The thin film chip capacitor was selected from the Murata manufacturing company. Method of moments based IE3D software is used for that study. The simulated and measured return losses of antennas with and without lump elements are plotted in Figure 7. The frequency has a shift between simulation and measurement results. We think it is caused by fabrication tolerance and the effect of the connector

Table 1: 3D radiation pattern measurement results of the antenna without and with lump elements.

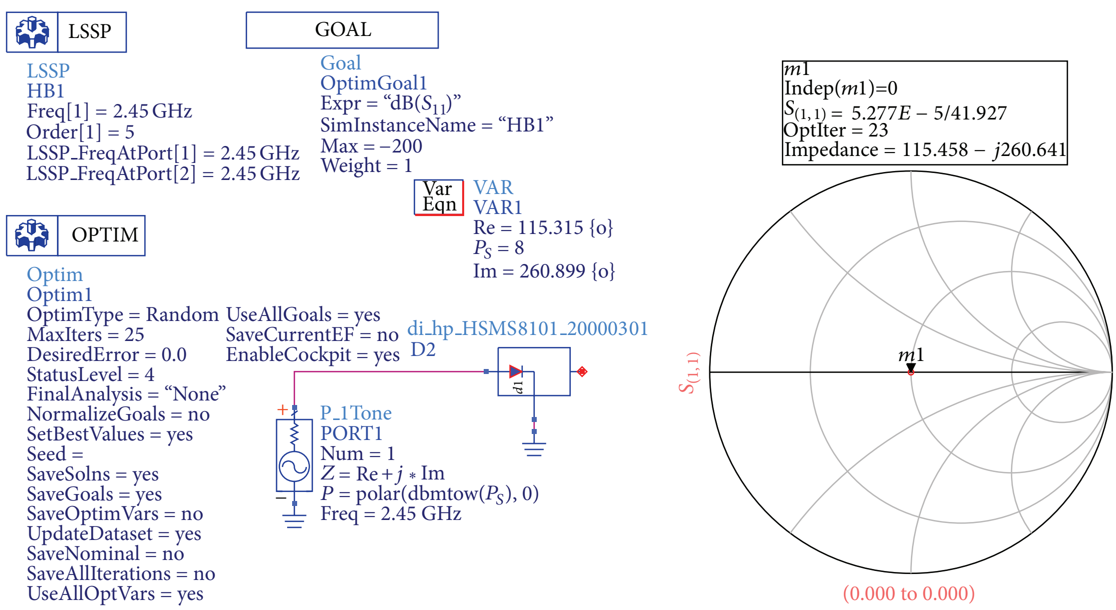
Frequency (Mhz)	Antenna without lump elements	Antenna with lump elements
2700		
2800		
2900		

used in the measurement. Otherwise, from each result of simulation or measurement, the performances of antennas with and without lump elements are almost identical. The similar 3D radiation pattern measurement results between the antenna with and without lump elements can be observed in Table 1. Table 2 further shows the measured peak gain and antenna efficiency of the antennas with and without lump elements. Based on the above results in both simulation and measurement, inserting the lump elements into the proposed positions of the antenna does not greatly affect the antenna performances.

2.4. Rectenna Design Methodology. To guarantee this novel topology rectenna system, a proposed rectenna in the industrial, scientific, and medical (ISM) frequency of 2.45 GHz is designed and fabricated on the 0.54 mm-thick Teflon substrate (dielectric constant = 2.54) with 0.018 mm copper

Table 2: Peak gain and efficiency measurement results of the antenna without and with lump elements.

Antenna	Without lump elements		With lump elements	
Frequency (MHz)	Peak gain (dBi)	Efficiency (%)	Peak gain (dBi)	Efficiency (%)
2,700	3.941	85.87	3.942	86.662
2,725	3.472	78.52	3.388	79.276
2,750	3.502	79.707	3.363	80.279
2,775	2.655	77.45	2.862	77.892
2,800	3.335	91.783	3.372	91.779
2,825	3.092	89.016	3.257	89.107
2,850	3.547	96.022	3.491	95.298
2,875	3.18	87.518	3.015	86.662
2,900	3.504	91.554	3.115	91.051



(a) (b)

Figure 8: (a) Setup for calculation of the conjugate matching impedance of the diode and (b) the calculated conjugate matching impedance of the diode in Smith chart.

cladding. A Murata 2.5 pF chip capacitor is used for better insertion loss at 2.45 GHz. The performance of the selected chip capacitor was evaluated by the tools from Murata manufacturing. A Schottky Mixer Diode (HSMS-8101) is used as the rectifying device. The general design flow begins by studying the diode impedance. In this work, Agilent Advanced Design System (ADS) 2009 is used to find the diode matching impedance at the specified power level. The large signal simulation setup is shown in Figure 8. In this study, the received power of 8 dBm is chosen for calculating the conjugate matching impedance of the diode. When the conjugate matching condition is reached, the calculated diode impedance is 115.461-j260.633 Ohm. After that the conjugate matching impedance for antenna is determined. Then the desired impedance of antenna with lump elements is optimized by tuning the value of L, $w1$, $w2$, and H in Figure 9. The total rectenna system including chip capacitor and load resistor is finally optimized by Full-wave EM simulator IE3D based on the method of moments. The detailed sizes of the two designed rectennas are tagged in Figure 9. The S11 result with renormalizing to the port impedance of 115.461-j260.633 is shown in Figure 10(a). We can see that the second harmonic signal is already rejected. A gain of 2.05 dBi is obtained at 2.45 GHz from the simulation. The radiation pattern of the rectenna simulated by IE3D is shown in Figure 10(b), which is very similar to that of a normal dipole antenna. Based on the design and optimization process, we observed that the introduced super-strip line also has some contribution to the impedance tuning. On the other hand, even the wideband folded dipole antenna has a large impedance tuning ability. The diode should be carefully selected. When the diode impedance is in the matching range of the antenna, the final optimization will be very fast and effective. The working impedance of the diode is sensitive in wireless power transfer.

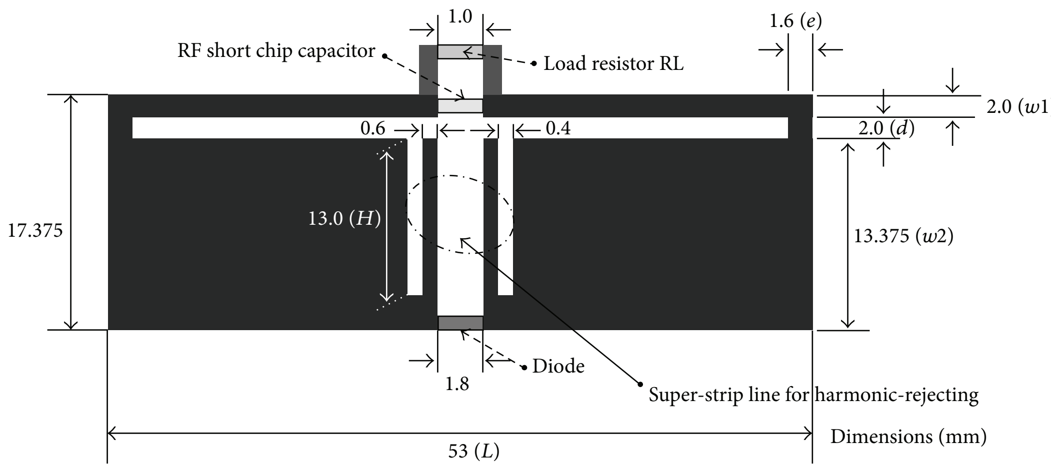


Figure 9: The geometry with detailed size of the proposed novel topology rectenna.

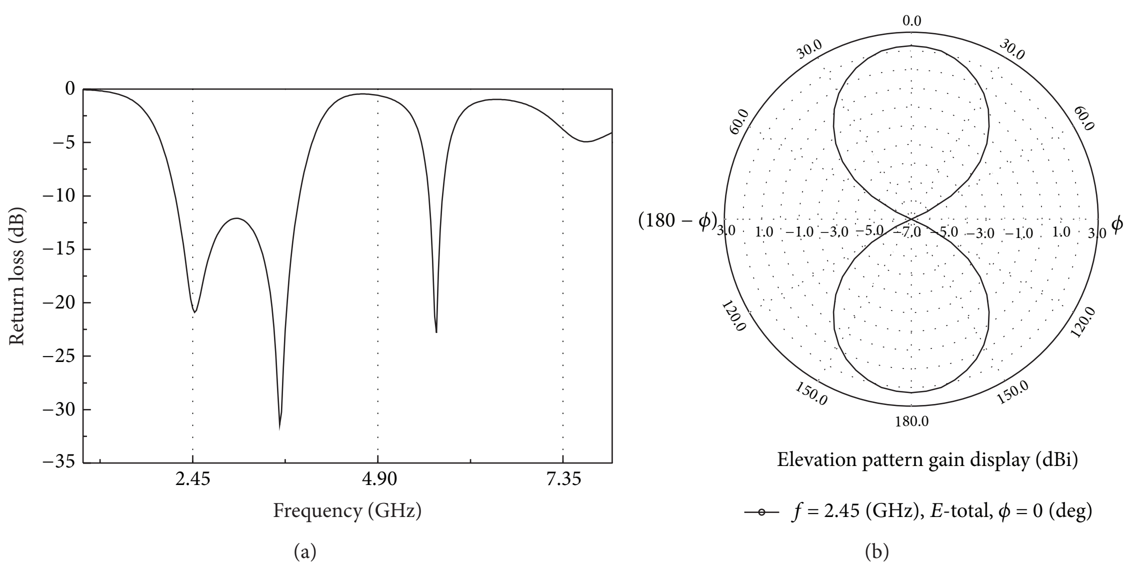


Figure 10: (a) Return loss of the 2.45 GHz rectenna with renormalized port impedance and (b) the simulated rectenna radiation pattern at 2.45 GHz.

Another advantage of using the wideband folded dipole is that the wideband feature decreases the matching tolerance between antenna and diode in the operation.

3. Experiment

The measurement setup and conversion efficiency calculation are followed by [14] except a 9.8 dBi 2 × 2 patch array which replaced the horn antenna as the transmitting antenna. The size of the realized 2 × 2 patch array antenna working at 2.45 GHz is 122 × 122 mm^2. Agilent 83620B signal generator, 30 dB power amplifier, 10 dB attenuator, and 10 dB directional coupler are used in the measurement to supply the transmission RF power. A DC voltage meter with 100 Ohm load resistor is used for measuring the output DC voltage from the rectenna. The rectenna is localized in the far field zone $((2 \cdot D^2/\lambda_0) > 0.25\,\mathrm{m})$ at a distance of 1.2 m from the 2 × 2 patch array. The RF-to-DC conversion efficiency is defined as

$$\eta = \frac{(V_{\mathrm{DC}})^2/R_L}{P_{\mathrm{received}}}. \quad (1)$$

Finally, the output voltage is measured and the conversion efficiency is calculated and plotted in Figure 11. Measured bandwidth is about 400 MHz to keep the efficiency higher than 70% in the frequency range from 2.4 GHz to 2.8 GHz. Table 3 provides a comparison of size and conversion efficiency between proposed rectenna and other published rectennas working at 2.45 GHz. Most of the conventional rectennas consist of antenna part and rectifying circuit part. When the frequency is low, the size of the antenna is the main factor in the total size of the rectenna. When the frequency is high, the size of the rectifying circuit often takes much area in the total rectenna system. Carefully selecting the diode, the

Table 3: Comparison of this work with several published work.

Frequency (GHz)	Reference	Planes used	Dielectric constant	Size (mm^2)	Conversion efficiency
2.45	[9]	2	2.2	99 × 91	75%
2.45	[15]	2	2.33	100 × 50	77.8%
2.45	[16]	3	4.4	60 × 60	75%
2.45	[17]	2	2.2	160 × 50	84%
2.45	This work	1	2.54	53 × 20	72.9%

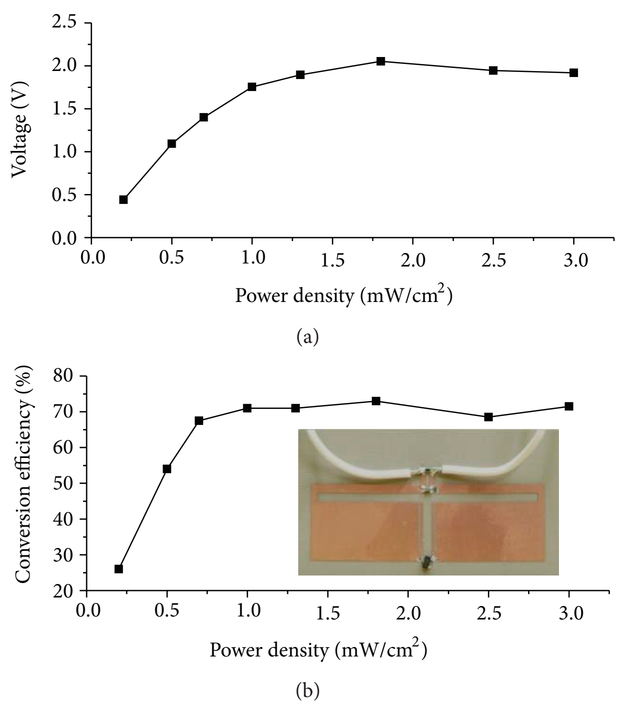


Figure 11: (a) Measured DC output voltages and (b) calculated conversion efficiencies.

proposed rectenna architecture can be very compact in both low and high microwave frequency range.

4. Conclusion

In this work, a compact rectenna with a novel topology has been developed. By using a wideband folded dipole antenna, large impedance tuning ability can be achieved. The proposed novel compact rectenna saves the matching network by directly connecting the antenna with the diode. A pair of super-strip lines is introduced in the wideband folded dipole to reject the second harmonic signal, which further saves the components from the normal rectenna system. Most important is that through decomposition and recombination, a novel rectifying circuit has been self-embedded in the proposed rectenna. The area of the proposed novel rectenna topology is much less than that of the conventional rectenna. The proposed rectenna is very compact and low cost. Considering the above advantages, this novel topology rectenna is very suitable for small wireless harvesting applications.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This work was sponsored by Natural Science Foundation of Heilongjiang Province, China (no. QC2011C097), National Science Foundation of China (no. 61201017 and no. 51138003), and National 863 Foundation of China (no. 2012AA112310).

References

[1] K. M. Z. Shams and M. Ali, "Wireless power transmission to a buried sensor in concrete," *IEEE Sensors Journal*, vol. 7, no. 12, pp. 1573–1577, 2007.

[2] M. Sudou, H. Takao, K. Sawada, and M. Ishida, "A novel RF induced power supply system for monolithically integrated ubiquitous micro sensor nodes," *Sensors and Actuators A*, vol. 145-146, no. 1-2, pp. 343–348, 2008.

[3] M. A. Adeeb, A. B. Islam, M. R. Haider, F. S. Tulip, M. N. Ericson, and S. K. Islam, "An inductive link-based wireless power transfer system for biomedical applications," *Active and Passive Electronic Components*, vol. 2012, Article ID 879294, 11 pages, 2012.

[4] J.-Y. Park, S.-M. Han, and T. Itoh, "A rectenna design with harmonic-rejecting circular-sector antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 3, no. 1, pp. 52–54, 2004.

[5] T.-C. Yo, C.-M. Lee, C.-M. Hsu, and C.-H. Luo, "Compact circularly polarized rectenna with unbalanced circular slots," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 3, pp. 882–886, 2008.

[6] L. W. Epp, A. R. Khan, H. K. Smith, and R. Peter Smith, "A compact dual-polarized 8.51 GHz rectenna for high-voltage (50 V) actuator applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 48, no. 1, pp. 111–120, 2000.

[7] M. Ali, G. Yang, and R. Dougal, "A new circularly polarized rectenna for wireless power transmission and data communication," *IEEE Antennas and Wireless Propagation Letters*, vol. 4, no. 1, pp. 205–208, 2005.

[8] H. J. Visser, J. Theeuwes, M. Van Beurden, and G. Doodeman, "High-efficiency RF-rectenna design," *EDN*, vol. 52, no. 14, p. 34, 2007.

[9] A. Douyère, J. D. Lan Sun Luk, and F. Alicalapa, "High efficiency microwave rectenna circuit: modelling and design," *Electronics Letters*, vol. 44, no. 24, pp. 1409–1410, 2008.

[10] J. O. McSpadden, L. Fan, and K. Chang, "Design and experiments of a high-conversion-efficiency 5.8 GHz rectenna," *IEEE Transactions on Microwave Theory and Techniques*, vol. 46, no. 12, pp. 2053–2060, 1998.

[11] B. Strassner and K. Chang, "5.8 GHz circularly polarized rectifying antenna for wireless microwave power transmission," *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, no. 8, pp. 1870–1876, 2002.

[12] Y.-J. Ren and K. Chang, "Bow-tie retrodirective rectenna," *Electronics Letters*, vol. 42, no. 4, pp. 191–192, 2006.

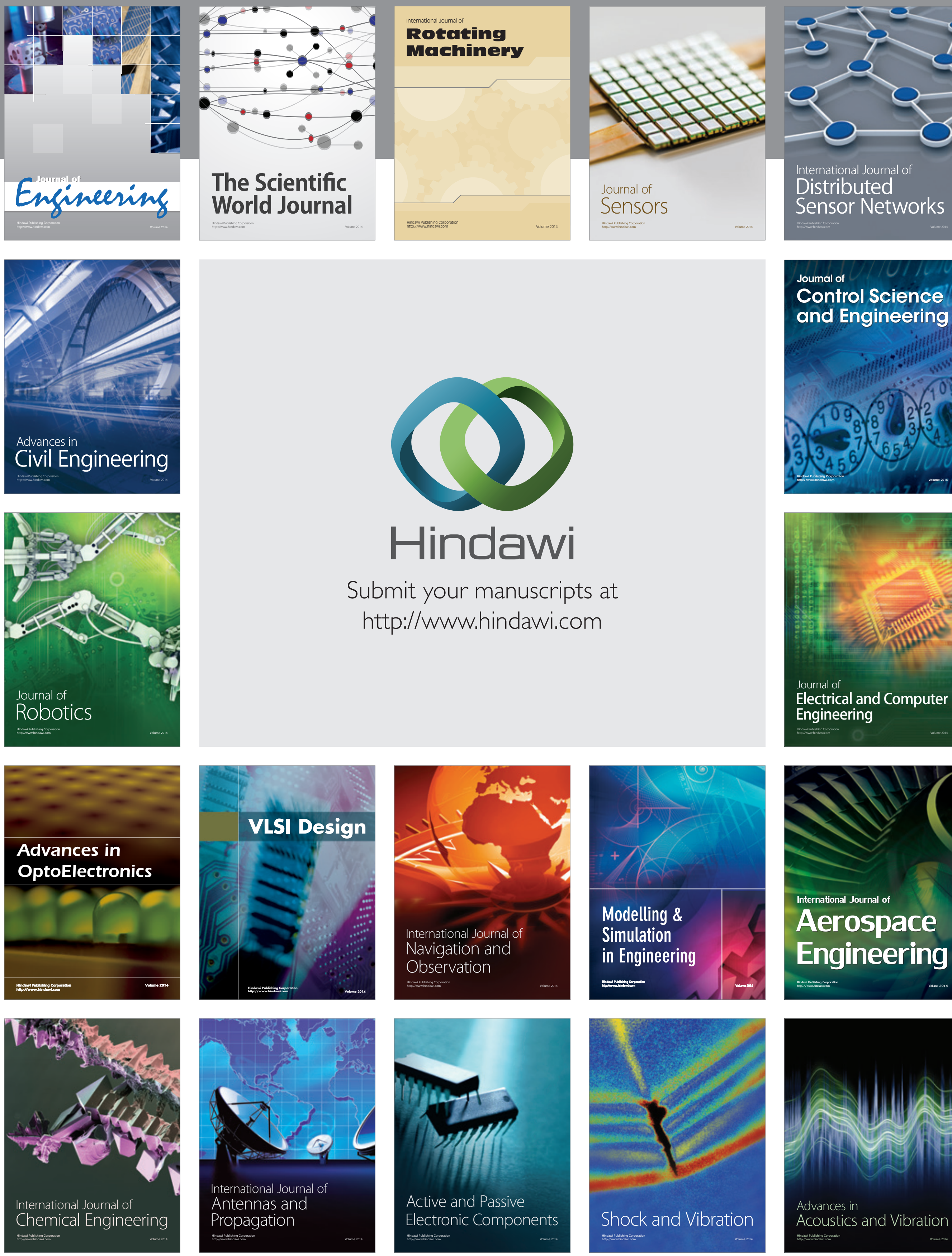
[13] S. Tanaka, Y. Kim, H. Morishita, S. Horiuchi, Y. Atsumi, and Y. Ido, "Wideband planar folded dipole antenna with self-balanced impedance property," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 5, pp. 1223–1228, 2008.

[14] Y.-H. Suh and K. Chang, "A high-efficiency dual-frequency rectenna for 2.45- and 5.8 GHz wireless power transmission," *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, no. 7, pp. 1784–1789, 2002.

[15] J.-Y. Park, S.-M. Han, and T. Itoh, "A rectenna design with harmonic-rejecting circular-sector antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 3, no. 1, pp. 52–54, 2004.

[16] Y.-J. Ren, M. F. Farooqui, and K. Chang, "A compact dual-frequency rectifying antenna with high-orders harmonic-rejection," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 7, pp. 2110–2113, 2007.

[17] H. Takhedmit, L. Cirio, O. Picon, C. Vollaire, B. Allard, and F. Costa, "Design and characterization of an efficient dual patch rectenna for microwave energy recycling in the ISM Band," *Progress in Electromagnetics Research C*, vol. 43, pp. 93–108, 2013.


Journal of Engineering
The Scientific World Journal
International Journal of Rotating Machinery
Journal of Sensors
International Journal of Distributed Sensor Networks
Advances in Civil Engineering
Hindawi
Submit your manuscripts at
http://www.hindawi.com
Journal of Control Science and Engineering
Journal of Robotics
Journal of Electrical and Computer Engineering
Advances in OptoElectronics
VLSI Design
International Journal of Navigation and Observation
Modelling & Simulation in Engineering
International Journal of Aerospace Engineering
International Journal of Chemical Engineering
International Journal of Antennas and Propagation
Active and Passive Electronic Components
Shock and Vibration
Advances in Acoustics and Vibration