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Ambient RF Energy Harvesting System Based on Wide Angle Metamaterial Absorber for Battery-Less Wireless Sensors

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Ambient RF Energy Harvesting System Based on Wide Angle Metamaterial Absorber for Battery-Less Wireless Sensors

Quang Minh Dinh, Minh Thuy Le*
Department of Instrumentation and Industrial Informatics, School of Electrical Engineering
Hanoi University of Scienes and Technology
Hanoi, Vietnam
minh.dq162700@sis.hust.edu.vn; thuy.leminh@hust.edu.vn
Corresponding author: Minh Thuy Le; Email: thuy.leminh@hust.edu.vn

Abstract––**In this paper, a wide – angle rectenna based on metamaterial absorber is proposed. By using the absorbing surface consists of multiple periodically arranged unit cells, the proposed ambient RF energy harvesting device can power sufficient DC power for a wireless sensor from the ambient RF sources in environment. The rectifiers employed in this rectenna system are optimized to have a RF-DC conversion efficiency of 38% and 50% at very low input power of -10 dBm and -5 dBm, respectively. The symmetric unit cells are designed to yield a high absorptivity at wide incident angle in both H plane and E plane and by attaching two rectifiers for each one of them, the device is able to achieve a wide – angle dual – polarized operation up to 140 degrees. Numerical simulations are conducted to validate the design while a comparison to previously introduced rectennas is also provided to elucidate the advantages of the ambient RF energy harvesting system in this work.**

Keywords** – RF energy harvesting, rectennas, metamaterial absorber, wide angle incident, low incident power.

I. INTRODUCTION

As low – powered wireless devices such as wireless sensors gradually becoming more and more pervasive, the demand for a sustainable power supply appears is also increasing. Up to now, most wireless electronic devices still use batteries as their primary power sources which led to some disadvantages like bulky size and weight, regular maintenance due to limited lifespan and also environmentally unfriendly [1]. Instead of using batteries, other power sources available in the ambient environment such as solar, thermal gradient, vibration or RF waves can be collected to sustain devices' operations. Out of those above options, RF waves stands out as a suitable candidate despite not having a high power density, due to their ubiquity, weather independence and all – time availability [2].

In ambient environment, where power density can be as low as several μW/cm^2 or sometimes even lower than 1μW/cm^2 [2-3] while a low power sensor node consume several mW to sustain its operation, rectenna with a single antenna can barely collect enough power for any device. Therefore, multiple antennas, or so – called array, are used to increase the amount of power harvested. The collected power in each antenna element will be either combined using RF power combiner then delivered to a single rectifier or rectified then combined. The former combining method namely RF – combine yields high efficiency at normal incidence but performs poorly at oblique incident angle while the later DC – combine method can maintain a more stable operation at wider angle [4-5]. More specifically, in [3], two rectenna arrays from both methods were investigated under the same input power. The RF – combine array saw its output DC power plummeted from approximately -5dBm to -10dBm as the incident angle widened to 20^o while the DC – combine one maintained a relatively stable output power, only decreased from -8dBm to -10dBm as the angle increased to 60^o. In practical situation, incident waves come from any direction, it can be directly from a base station or reflected from buildings. As the directions of incoming waves are unknown, rectennas are required to maintain their performance under wide incident angle, the second method will therefore be more suitable. The angle dependency is usually described using the parameter Half – power beam width (HPBW). To the best of our knowledge, up to date, few rectenna arrays can yield wide beam (wider than 100^o) in both E plane or H plane [6-9].

Since diodes consume a certain amount of power, at low input power, the loss on diodes may overwhelm the DC power obtained. Rectenna thus has to fulfil another requirement: to achieve a high conversion efficiency at low incident power as in ambient environment, typically ranging from -10 to -20 dBm [1]. To the best of our knowledge, most of previously introduced rectennas achieve efficiency at - 10dBm input power ranging from 20% to 55% [7-11].

To satisfy the demand for a rectenna with sufficient collected power at incident power as low as - 10dBm, all polarizations, incident angle - independence for practical use, in this paper, a metamaterial absorber which acts as a receiving antenna array is employed. The absorber yielding a near – perfect absorption is optimized to have most of its absorbed power transformed into AC rather than wasted away in the form of heat loss like in traditional metamaterial absorber thus achieve high RF – AC conversion efficiency. Each metamaterial unit cell is equipped with its own rectifier to achieve angle stability. The rectifiers are designed efficiently convert AC into DC at low input power.

II. METAMATERIAL ABSORBER DESIGN

The metamaterial absorber consists of multiple periodically arranged unit cells, each formed by 5 layers as

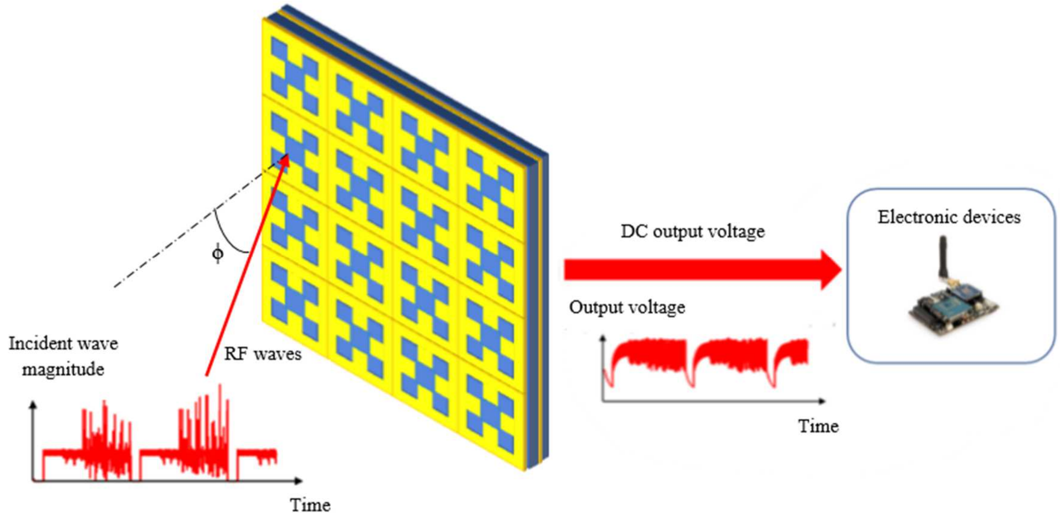

Fig. 1. The energy harvesting system and its output voltage in real life application where the incident waves are modulated.

shown in Figure 2. The resonator (Figure 2a) occupies the front face, followed by a dielectric substrate, the ground plane with two apertures for feeding purpose, another dielectric layer and finally the two feed lines and rectifiers at the bottom. The two rectifiers are designated in the area between adjacent unit cells but for simplicity, they are not depicted and instead replaced by two lumped ports *1* and *2* having the same 50Ω input impedance. The concepts of incident angle Θ is also introduced in Figure 2. The dimensional parameters of a unit cell are P = 36 mm, W_{m1} = 4.5mm, W_{m2} = 3mm, G = 6 mm, W_f = 1 mm, L_f = 16 mm, L_a = 2 mm, W_a = 9 mm, A = 9 mm, H_1 = 2.54 mm, H_2 = 0.8 mm.

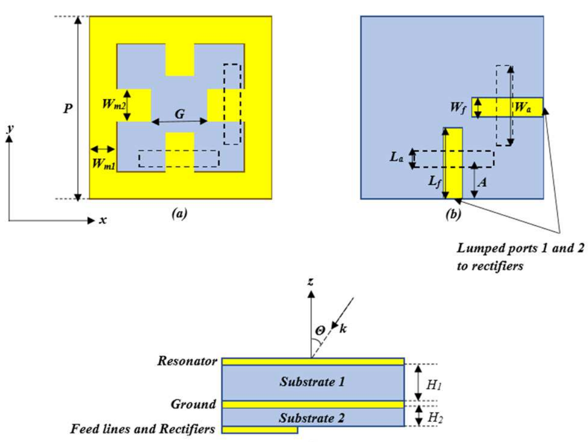

Fig. 2. Structure of a unit cell of the proposed rectenna. (a), (b), (c) are the front, back and side view, respectively.

When an external electric field is applied to the absorber, induced currents appear on the surface of each unit cell with the distribution shown in Figure 3 The black arrows represent the external electric and magnetic fields, the red solid arrows are the currents and the red dash arrows are the electric fields occupy the gap in the middle line. The highest current intensity is achieved at resonant frequency where power accepted into the structure is maximum. The length of each cell P is the main factor deciding the resonant frequency which is 3.75GHz in this case corresponding with 5G source, while the widths of microstrip lines and the gaps, which contributes to the structure's input impedance, is optimized to match with free – space thus obtain near – perfect absorption.

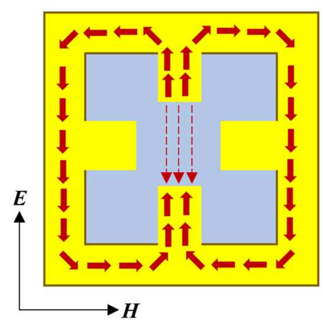

Fig. 3. A close representation of induced currents and electric fields' distribution on the unit cell.

In conventional metamaterial absorber, where absorption is the primary concern, absorbed power is dissipated into heat. Here by introducing two apertures on the ground layer, coupling mechanism allows collected power to be transferred to the other side of the ground and into feed lines as AC [6]. The apertures act as matching circuits between cells and feeds, they are placed under the middle lines where the currents converge and have their dimensions optimized so that most of the absorbed power are transformed into AC and delivered to the feed lines. The symmetric nature of the resonator ensures polarization independence, which are crucial in practical applications. The materials for both substrates are chosen to be Duroid5880 with the permittivity of 2.2 and a very low loss tangent of 0.0009 thus ensures minimal dielectric loss.

The RF – to – AC conversion efficiency is investigated using CST software. The boundary condition is set to *unit cell* while a Floquet port called Z_{max} excites plane waves to the rectenna. The RF – AC efficiency will then be calculated from the simulated S - parameters as follow:

$$\eta_{RF-AC} = |S_{Zmax,1}|^2 + |S_{Zmax,2}|^2 \qquad (1)$$

The result is displayed in Figure 4. Under normal incidence, the structure achieves the highest RF – AC efficiency of 93%. In H plane, it remains highly absorptive under angle as wide as 60° with the efficiency higher than 80%. In E plane, despite experiencing some slight frequency shift, the efficiency remains stable around 90%.

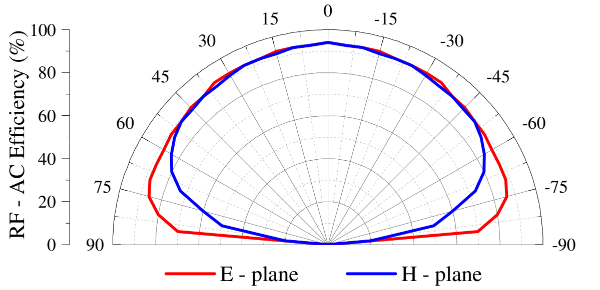

Fig. 4. Simulated RF – AC efficiency at different incident angle in E plane and H plane.

III. Metamaterial Harvester Design

The rectifiers circuit in this work consists of multiple half – wave voltage doubles parallelly connected as shown in Figure 5. One unique feature of metamaterial rectennas is that the unit cells are usually arranged very closely thus a peculiar requirement for the rectifiers arises: while compactness is not mandatory for single antenna, in metamaterial structure, rectifiers must be small enough to stay fit inside the limited area between adjacent cells. In this work, as the metamaterial absorber are symmetric thus achieves polarization independence, two rectifiers will have to be attached to each unit cell. The importance of compactness is therefore evident.

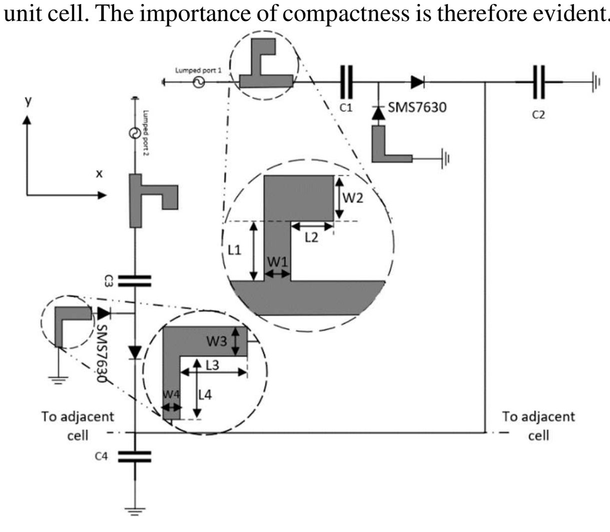

Fig. 5. Two rectifiers of each unit cell. Dimensions: L_1 = 5 mm, W_1 = 1.2 mm, L_2 = 3 mm, W_2 = 3.2 mm, L_3 = 5.5 mm, W_3 = 1 mm, L_4 = 3.5 mm, W_4 = 1.4 mm. The values of all four capacitors are 22pF.

To reduce the rectifier's size, the open matching stub and the microstrip line that grounds the first diode are bended 90° thus shortens the lengths in one direction while accepting the lengthening in the other. The SMS7630 Schottky diode is selected due to its high performance at low input power [7].

The design and simulation processes are conducted in ADS software for a single unit cell alone, with the diode formulated using SPICE model. The RF – DC efficiency will be calculated as follow:

$$\eta_{RF-DC} = \eta_{RF-AC} \cdot \frac{{V_{DC}}^2}{R_L} \qquad (2)$$

where V_{DC} is the output DC voltage and R_L is the load impedance for each unit cell. It is worth noticing that while the optimal load for each unit cell R_L can be several kΩ, as the cells are parallelly linked, the optimal load for the entire structure will be R_L/n where n is the number of cells in order to achieve the same efficiency. The geometrical dimensions of the rectifiers are optimized to achieve a good agreement between performance and compactness while the load impedance is chosen to yield highest achievable RF – DC efficiency. The simulation results are shown in Figure 6 and Figure 7.

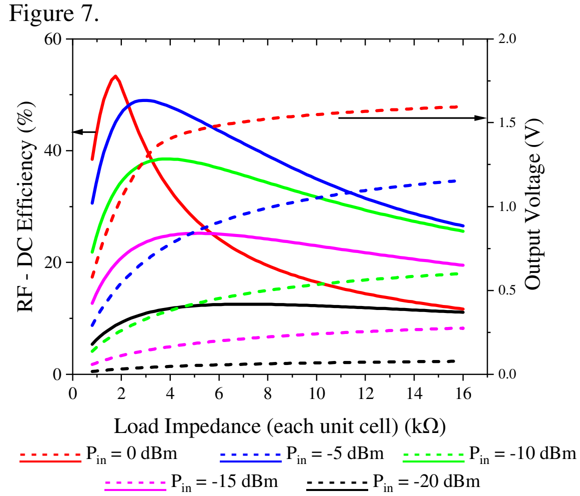

Fig. 6. Simulated RF – DC efficiency and output DC voltage as a function of load impedance at different input powers P_{in}.

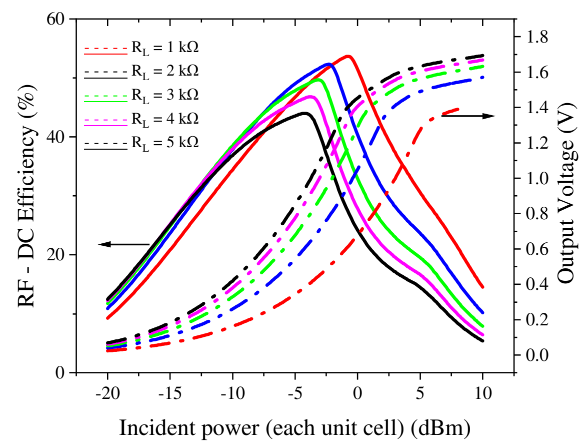

Fig. 7. Simulated RF – DC efficiency and output DC voltage as a function of load impedance at different input power levels.

The ability to withstand wide incident angle is also investigated in simulation. In antenna arrays, the culprit behinds their narrow beam is the phase mismatch between element antennas. For the metamaterial in this work, the difference in phase between adjacent unit cell can be calculated as follow:

$$\Delta\phi = \frac{2\pi.P.sin\theta}{\lambda} \tag{3}$$

where P is the cell – to – cell distance, Θ is the incident angle and λ is the free – space wavelength. An array consists of 4 x 4 rectifiers, with the total size of 16 cm x 16 cm, is simulated with their phases modelled using Equation (3). In general, the AC – DC efficiency remains virtually the same with different incident angles. Therefore, the RF – DC efficiency as a function of incident angle can be expressed as:

$$\eta_{RF-DC}(\Theta, P_{in}) = \eta_{RF-AC}(\Theta).\eta_{AC-DC}(P_{in}) \tag{4}$$

and the simulated angle dependency is depicted on Figure 8. It is clear that the rectenna possesses a wide beam width as expected, nearly 150º in H plane and more than 160º in E plane.

Moreover, one can easily calculate from Figure 8 the output DC power obtained from the 4 x 4 harvester. For example, it obtains a DC output of 2.5 mW at -5 dBm (or 0.32 mW input power) and 0.64 mW at -10 dBm (or 0.1 mW) input power. Those collected powers are, in theory, sufficient to supply some low power sensor nodes such as CC2650 or nRF52811 which consume from several µW to ≈ 10 mW, depend on the operating modes [8-9]. By further increasing the number of unit cells, this structure can, in theory, comfortably supply those low power sensor nodes.

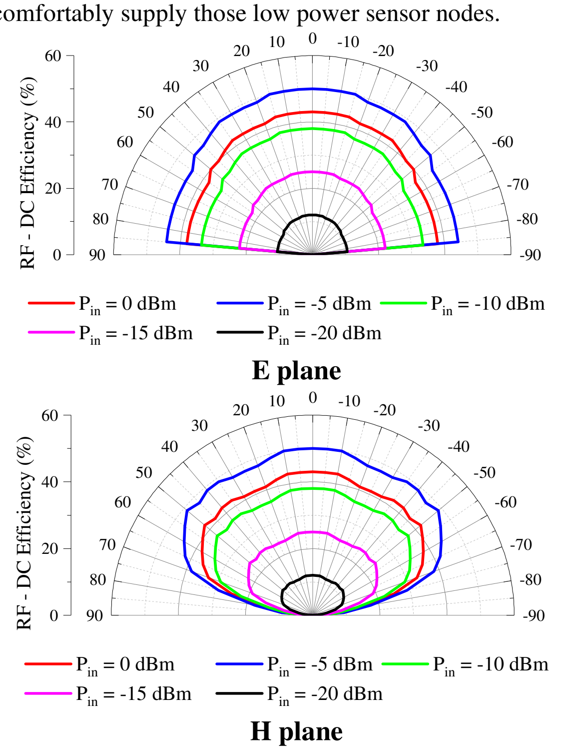

Fig. 8. Simulated RF – DC efficiency as a function of incident angle in E and H plane, R_L is chosen to be 125 Ω (2 kΩ for each cell).

IV. A Comparison to Previous Works

To further elucidate the advantages of the metamaterial – based rectenna in this work, a comparison between it and some previously introduced rectenna arrays is provided in Table 1. The criteria are conversion efficiency, the ability to perform well at low input power and the ability to withstand wide incident angle.

It is apparent that the device here can not only provide a good efficiency at low input power but also maintain that performance at wide incident angle in both H plane and E plane. That beneficial characteristic is achieved thanks to the DC – combining method with each unit cell equipped with its own rectifiers while in other works where the element antennas are linked using RF – combining method, the beam widths are obviously narrow and thus their performance will be greatly affected as the incident angle deviates from 0º, the reason has been previously explained in the above sections.

TABLE I. A Comparison of This Works And Previous Works

Ref.	Freq. (GHz)	Input power (dBm)	Power density (W/m^2)	Eff. (%)	HPBW
[4]	1.84	-10	-	45	30º – E plane 170º – H plane
	2.14	-10	-	50	20º – E plane 110º – H plane
[5]	5.8	-	0.041	45	≈ 30º (appx.)
[10]	5.8	-	0.03	38	≈ 25º (appx.)
[11]	5.8	15.2	-	70	39.3º – H plane
This work	3.75	-10	0.0625	39	**> 140º – H plane > 160º – E plane**

a. (appx: approximated from the figures provided, Eff: efficiency)

V. Conclusion

In this work, we introduced and numerically investigated a rectenna using metamaterial absorber. The polarization independence is obtained thanks to the symmetry of the unit cells. By employing the absorber and having each one of its unit cell equipped with their own rectifiers, the device was able to achieve a wide – angle operation in addition to the ability to perform well at low input power. More particularly, a 38% RF – DC efficiency is achieved at -10dBm input power and that efficiency remains relatively stable at incident angle up to 60º in H plane and 80º in E plane. With such advantages, the proposed rectenna is suitable to be used in practical application where both efficiency and angle insensitiveness are required.

ACKNOWLEDGMENT

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REFERENCES

[1] D.-K. Ho, I. Kharrat, V.-D. Ngo, T.-P. Vuong, Q.-C. Nguyen, and M.-T. Le, 'Dual-band rectenna for ambient RF energy harvesting at GSM 900 MHz and 1800 MHz', in *2016 IEEE International Conference on Sustainable Energy Technologies (ICSET)*, Hanoi, Vietnam, Nov. 2016, pp. 306–310.

[2] M. Cansiz, D. Altinel, and G. K. Kurt, 'Efficiency in RF energy harvesting systems: A comprehensive review', *Energy*, vol. 174, pp. 292–309, May 2019.

[3] U. Olgun, Chi-Chih Chen, and J. L. Volakis, 'Investigation of Rectenna Array Configurations for Enhanced RF Power Harvesting', *IEEE Antennas Wirel. Propag. Lett.*, vol. 10, pp. 262–265, 2011.

[4] H. Sun, Y. Guo, M. He, and Z. Zhong, 'A Dual-Band Rectenna Using Broadband Yagi Antenna Array for Ambient RF Power Harvesting', *IEEE Antennas Wirel. Propag. Lett.*, vol. 12, pp. 918–921, 2013.

[5] T. Matsunaga, E. Nishiyama, and I. Toyoda, '5.8-GHz Stacked Differential Rectenna Suitable for Large-Scale Rectenna Arrays With DC Connection', *IEEE Trans. Antennas Propag.*, vol. 63, no. 12, pp. 5944–5949, Dec. 2015.

[6] D. M. Pozar, 'Microstrip antenna aperture-coupled to a microstripline', *Electron. Lett.*, vol. 21, no. 2, p. 49, 1985.

[7] S. Hemour *et al.*, 'Towards Low-Power High-Efficiency RF and Microwave Energy Harvesting', *IEEE Trans. Microw. Theory Tech.*, vol. 62, no. 4, pp. 965–976, Apr. 2014.

[8] Texas Instruments, 'CC2650 SimpleLink™ Multistandard Wireless MCU'. Feb. 2015.

[9] Nordic Semiconductor, 'nRF52811 Datasheet'. Feb. 2019.

[10] T. Sakamoto, Y. Ushijima, E. Nishiyama, M. Aikawa, and I. Toyoda, '5.8-GHz Series/Parallel Connected Rectenna Array Using Expandable Differential Rectenna Units', *IEEE Trans. Antennas Propag.*, vol. 61, no. 9, pp. 4872–4875, Sep. 2013.

[11] H. Sun and W. Geyi, 'A New Rectenna Using Beamwidth-Enhanced Antenna Array for RF Power Harvesting Applications', *IEEE Antennas Wirel. Propag. Lett.*, vol. 16, pp. 1451–1454, 2017.