Enhancement of Rectenna Performance using Artificial Magnetic Conductor for Energy Harvesting Applications

M. Abu, M. S. A. Jamil Kher, N. H. Izahar, A. F. Ab. Latif, S. N. Zabri
Center for Telecommunication Research and Innovation (CeTRI)
Faculty of Electronic & Computer Engineering
Universiti Teknikal Malaysia Melaka (UTeM),
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka.
maisarah@utem.edu.my

***Abstract*—This paper brings together an understanding on Artificial Magnetic Conductor (AMC) and rectenna in energy harvesting applications. The rectenna is built upon a combination of a low profile antenna like dipole or patch microstrip with the presence of a rectifying circuit as well as a filter to act as an RF to DC converter. In wireless power transmission, the focal problem is that the total capture of the RF energy is totally low. Thus, with the aim of capturing maximum power, the receiving antenna is supposed to be designed applicably by taking contemplation of several aspects especially the gain. AMC helps to improve the performance of an antenna, hence enhancing the execution of wireless power transmission system of the rectenna. Wireless sensor network is one of the application in wireless power transmission system that applied the approach of energy harvesting, where it is considered to be a practical and deployable solution for today's technology. Two designs of AMC had been proposed; a rectangular AMC using RO3003 substrate and a square AMC using RO3010 substrate. Simulation results show that the square AMC gives better performance through gain enhancement by 3.529 dB of a half-wave wire dipole antenna with an overall size of 122.45 mm x 122.45 mm.**

***Index terms*—AMC, Energy harvesting, Antenna, Rectenna, Rectifier.**

I. INTRODUCTION

In wireless power transmission, the electrical energy is transmitted from a power source to an electrical load, free from any artificial conductors. It is an attractive feature that offers transmitting power without any use of wires thus making it more convenient and less harmful. Different from wireless telecommunications, for example radio, wireless power transmission had its own difficulty that need to be overcome. If the transmission power are too low, the received energy tends to become critical as it is unable to differentiate the signal from background noise thus making the aspect of efficiency is the most core parameter in wireless power transmission. In order to increase the efficiency of the system, a rectenna with Artificial Magnetic Conductor (AMC) is introduced.

In wireless power transmission, the focal problem is the total capture of the RF energy is totally low. In order to capture maximum power, the receiving antenna ought to be designed appropriately by taking consideration of various factors such as antenna gain, return loss and efficiency [1]. With wireless power, efficiency is the most significant parameter. So, the rectenna is designed using Artificial Magnetic Conductor (AMC) to improve the wireless power transmission system [2]. Also known as High-Impedance Structure (HIS), AMC is an artificial, metallic, electromagnetic structure in which it was designed to be selective in backup surface wave currents that is different from conventional metallic conductors. Similar to its name, HIS or AMC has a very high impedance at its resonant frequency where at this point, waves are not tied to the surface [3]. It is generally described as an electromagnetic band gap (EBG) material or a type of synthetic composite that is purposely designed with a magnetic conductor surface for an apportioned, but defined range of frequencies. Theoretically, an efficient AMC would comply with its characteristics of having the reflection phase crosses zero at the resonant frequency due to the electromagnetically dual surface of an AMC to a perfect electric conductor (PEC) surface; PEC has reflection coefficient of $\Gamma = -1$ unlike AMC with $\Gamma = +1$ [3-9].

Rectenna is a special type of antenna in which under the category of rectifying antenna, applied to alter the microwave energy to direct current electricity [10-11]. Used to transmit power through radio waves, this rectenna is generally utilized in wireless power transmission system. One simple rectenna element builds up from a dipole antenna with an RF diode that linked through dipole elements. This RF diode rectifies the AC current induced in the antenna in form of microwaves which later produces DC power and then powering its load that connected across the diode. Commonly a Schottky diode is used due to its low voltage drop and high speed thus having the lowest power losses that are caused by the conduction and switching. Typically, a rectenna is built from an antenna as its RF power receiver, a low- or band-pass filter function as input filter to select the required signal as well as impedance matching simultaneously, a diode to rectify a device for RF-DC conversion, an output filter using bypass capacitor and lastly, a load resistance [12].

Many techniques of energy harvesting were introduced in order to develop a better discretion to the prevailing energy source. Likewise called as power harvesting or energy scavenging, this energy harvesting is a process in which energy was derived from external sources, for example solar energy, thermal energy, wind energy and etc.. These energies were captured and stored which is aimed at a small, wireless autonomous devices that had been used in one of those wearable electronics and wireless sensor networks. This implementation of energy harvesting onto wireless devices is a practical and deployable solution for today's technology.

II. Rectenna for Energy Harvesting

Nowadays, Wireless Sensor Network (WSN) has been catching attention from both industry and researchers as this kind of network can be utilized in various scenarios for instance intelligent office space, medical monitoring and military applications. WSN can be characterized for its low bit-rates, volume constraints for nodes also hundreds microwatts power consumption [13]. Radio frequency (RF) energy harvesting system architecture consists of rectenna (receiving antenna, matching network and rectifying circuit) and a load at the end. The mentioned rectenna required a high efficiency antenna to be able to capture sufficient RF wave to be converted to DC power through rectifying circuit. [11-15] shows literature on rectenna design for energy harvesting application.

Aya Mabrouki et. al. in [14] design a low-cost and efficient rectenna to resonate at $2.485\,GHz$ for microwave energy transfer. A Yagi antenna with a gain of $6dBi$ and return loss of $-17dB$ was applied as a receiving antenna and a single stage voltage double rectifier as the rectifying circuit. In addition, this rectifier was equipped with harmonic termination in order to increase the RF-to-DC conversion efficiency. The results showed 60% conversion efficiency with $17dBm$ input power and a 700Ω DC load. The measurement of the rectenna resulting in $2.25\,V$ DC output voltage and receiving a total power of $11dBm$ at a load of $1K\Omega$.

In [15], Noguchi et. al. introduced a small loop antenna and a high output voltage rectifier for a wide bandwidth in FM broadcasting application. The FM broadcast consist of two main signals, $81.9\,MHz$ with input power level of $-25dBm$ and $84.7\,MHz$ with input power level $-19dBm$. One rectenna in suburb area exhibits the output DC voltage of $924\,mV$ while a twin rectenna in series produces $1.72\,V$ of DC output voltage by accepting several FM broadcasting signals concurrently.

Paper [16] presented a study on the rectenna architecture for a low-power RFID application using energy harvesting technique in order to overcome the restriction of the necessity for battery replacement in a RFID tag. The antenna design in this system focuses at frequency of $2.4\,GHz$ band while the rectifier utilized a 7-stage Cockroft-Walton rectifying circuitry aiming at $30-50\%$ RF-to-DC conversion efficiency. Output results demonstrated an output DC voltage of $2V$ with $-4.881\,dBm$ $(0.325\,mW)$ of output power consuming an RF input power of $-4dBm$ $(0.398\,mW)$.

III. Artificial Magnetic Conductor

In order to increase the gain of one antenna, a high-permittivity dielectric superstrate or multilayer dielectric superstrate was once applied to the antenna. However, this superstrate increase the antenna height, thus resulting in a high-profile antenna. To overcome this problem, Artificial Magnetic Conductor (AMC) was introduced where the AMC not only decrease the antenna profile, but also maintain the high gain of the antenna [17-18]. Many literatures that studied on designing as well as analysis of AMC had been found in [4-6]. These papers analyze on the performance of the AMC in terms of its reflection coefficient and surface impedance as well as resonant frequency and bandwidth.

In [4], Dunbao Yan et. al. studied on a strip-type AMC structure to analyze its band gap characteristics. Initially, a mushroom-like Sievenpiper AMC structure was tested on the effect of patch size to the reflection phase band-gap. It is observed that the reflection phase band-gap for this structure is independent of the size in the direction perpendicular to polarization direction of incident plane wave. From this observation, a strip-type AMC structure was designed and accordingly, this type of structure exhibits the same independent behavior to its reflection phase as well as surface wave band-gap property. In addition, a strip-type AMC structure offers more advantages in terms of application on antenna and it is simpler to design and fabricate. This AMC utilized a substrate with a relative permittivity of 2.65 and a thickness of $2\,mm$ [4].

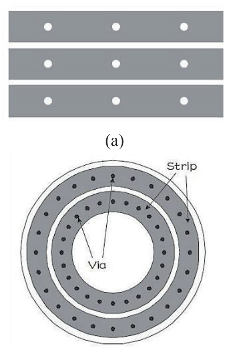


Figure 1: The AMC introduced in [4] (a) rectangular strip-type AMC (b) strip-type ringed AMC structure

A novel miniaturized AMC design utilizing interdigital capacitor was discussed in [6]. According to Hadarig et. al., the resonance frequency of an AMC depends on its geometry and dimensions, and also relative permittivity and thickness of the substrate used. Thus, he introduced two designs of AMC to produce two resonant frequencies of $4.15\,GHz$ and $6.2\,GHz$ as well as using two types of substrate, RO3010 ($\varepsilon_r = 10.2, h = 1.27\,mm$) and RO4003C ($\varepsilon_r = 3.38, h = 1.52\,mm$).

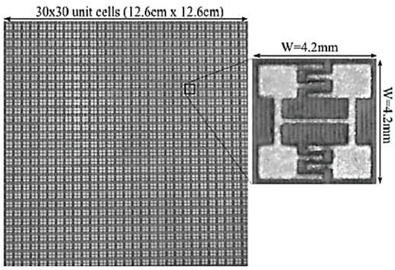
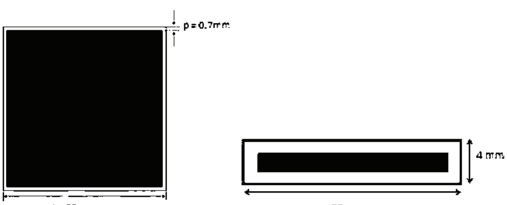


Figure 2: A 30 x 30 array of minituarized elements [6]

The first AMC used RO3010 and exhibits a reflection phase bandwidth of $100\ MHz$ (2.4%) while another AMC utilizes RO4003C, producing a bandwidth of $275\ MHz$ (4.4%). As predicted, the use of thicker substrate with lower relative permittivity in the second design resulted in bigger bandwidth and higher resonant frequency compare to the first design.

In [8], a design of AMC centering at $2.45\ GHz$ frequency was studied for metallic detection in RFID tag application. This paper introduced three structures of AMC; square AMC, rectangular AMC and Halfring AMC, where they were designed on a $1.52\ mm$ thick RO3003 substrate with a relative permittivity of 3. These three structures were inspected in terms of parameter effect through parametric studies to obtain highest performance. The reflection phase bandwidth at $\pm 90^{\circ}$ was focused as an important parameter with the resonant frequency of $2.45\ GHz$ fall at 0°. The basic square AMC gives a total bandwidth of 8.36%. However, the rectangular AMC while maintaining the same width as the square AMC resulted in lower percentage of bandwidth, 7.52%.



(a) (b)

Figure 3: Schematic and dimensions of two AMCs (a) Square AMC structure (b) Rectangular AMC structure [8]

The Halfring AMC on the other hand has the highest bandwidth of 13.86% by introducing additional vertical and horizontal gap.

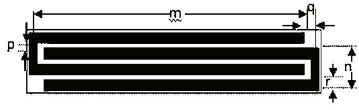
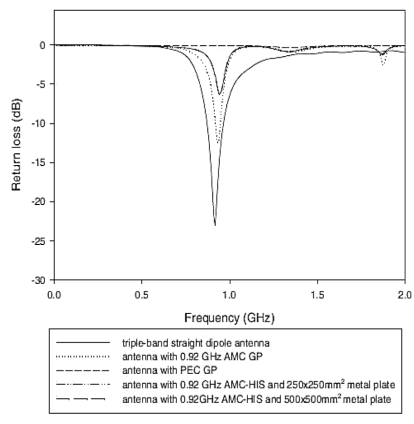


Figure 4: Schematic and dimensions of the proposed Halfring AMC structure where $m = 29\ mm$, $n = 4\ mm$

A frequency range of one AMC was determined from its reflection phase, thus showing AMC's characteristics to be observed. Consequently, both conventional mushroom-like EBG with via hole and the UC-EBG were tested. The in-phase reflection at a frequency of $2.45\ GHz$ can be seen on all surfaces. Thus, from both design structure investigated, the proposed design was introduced with the same characteristics from both design earlier but with more advantages as it utilizes no via hole making it a simpler structure and easy to fabricate as well as having a broad bandwidth.

To prove that AMC helps in enhancing the performance of one antenna, it was tested by attaching the planar AMC at the ground plane of an antenna. Paper [5] and [9] study on this particular topic using different designs of antenna. In [5], Zhang et. al. utilized a simple single patch and a patch array antenna as well as a planar AMC to investigate their relation plus explaining the function of an AMC in antenna operation. As mentioned earlier in the paper, this AMC ought to be able to reduce the parallel-plate modes that propagate between the plane with the coupling apertures and the backside reflector as its function as a field distributor and a transmission-line model. The antenna performance was compared in three conditions, without AMC, with AMC and with PEC. The numerical results illustrate that the antenna with AMC has a $6\ dB$ higher sidelobe suppression contrasted to the antenna with PEC.

As for [9], the single-band AMC was tested onto a triple-band printed dipole antenna for Radio Frequency Identification (RFID) application. The antenna performance was evaluated in terms of return loss, realized gain, radiation efficiency, radiation pattern and directivity. After being tested in those three bands of frequency centering at $0.92\ GHz$, $2.45\ GHz$, and $5.8\ GHz$, it can be perceived that the radiation properties of the antenna was improved. In addition, the realized gain, radiation efficiency and directivity increased considerably. Thus, this resulted dipole antenna with the presence of AMC is able to be used in metal object detection even the size of the metal plate attached was increased by upholding its properties.



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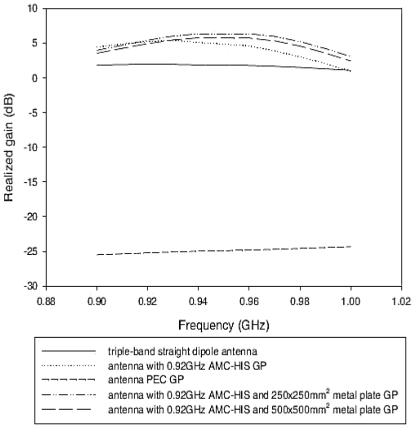

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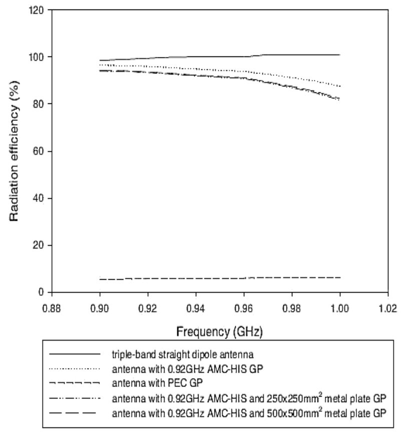


(c)

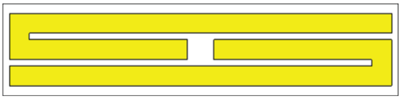
Figure 5: Simulated results of the antenna in various scenarios (a) Return loss (b) Realized gain (c) Radiation efficiency

IV. PROPOSED AMC DESIGNS

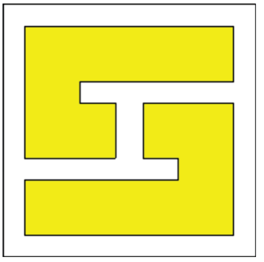
From the literature review done, a design of AMC for energy harvesting application was proposed focusing on its reflection coefficient and surface impedance at a center frequency of 2.45 GHz.

A. Artificial Magnetic Conductor (AMC) design structure

Figure 6(a) shows the designed 2.45 GHz AMC structure using dielectric with a permittivity of 3 and a thickness of 1.52 mm. The proposed design consists of a unit cell size of 30 mm x 7 mm with 3 layers; AMC patch, RO3003 substrate and a full ground plane.



(a)



(b)

Figure 6: 2.45 GHz AMC design structures (a) using RO3003 substrate; AMC-1 (b) using RO3010 substrate; AMC-2

In order to attain the center frequency of 2.45 GHz, the square patch had been cut into the shape as shown in Figure 6(b). The bigger the patch, the lower the center frequency, and vice versa. So, higher substrate permittivity was chosen for the second design where the RO3010 substrate with a permittivity of 10.2 and a thickness of 1.28 mm was used. Figure 6(b) presents the design of a unit cell 2.45 GHz AMC having a substrate size of 18.3 mm x 18.3 mm.

B. Results

AMC was designed for the purpose of increasing the antenna total efficiency or gain. Figure 7 presents the reflection phase as well as the surface impedance for a single unit square of the AMC that operates at a frequency of 2.45 GHz. The size of the substrate and patch give impact on the result in order to attain the actual resonant frequency.

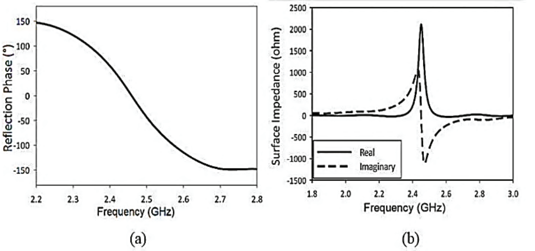
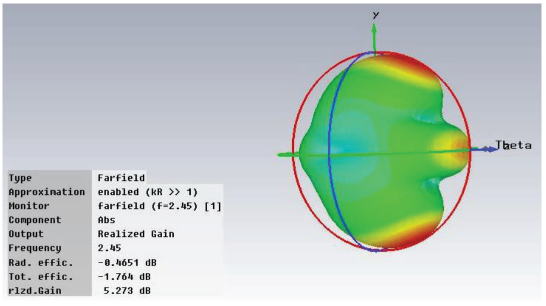
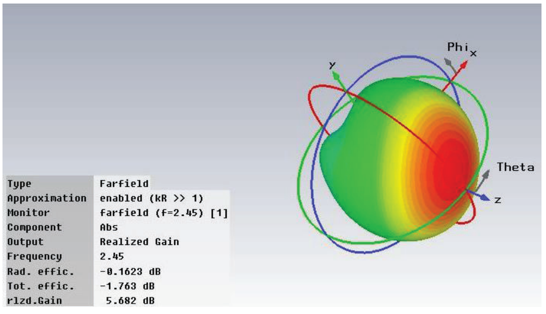


Figure 7: Simulated results of one square unit of AMC-2 (a) reflection phase (b) surface impedance

In Figure 7, it is shown that all AMCs satisfy the characteristic of a single unit cell AMC by having its reflection phase at 0° at the resonant frequency at 2.45 GHz. It is also comply with other characteristics of obtaining a very high surface impedance of $\geq 1000\Omega$ at the desired frequency (2.45 GHz). The working frequency of the first AMC is 2.37 GHz to 2.54 GHz which corresponds to 7% bandwidth. The performance of the half-wave wire dipole antenna is observed on 17x4 AMC-1 resulting on 5.273 dB of realized gain. Thus, about 3.12 dB of gain enhancement is recorded compare to the standard gain of half-wave dipole. While the working frequency of the second AMC is 2.40 GHz to 2.51 GHz which corresponds to 4.63% bandwidth. Figure 8(b) presents the realized gain for λ/2 wire dipole on a 6x6 unit cell of the second AMC at 2.45 GHz. Both AMCs have an overall size of 122.45 mm x 122.45 mm which correspond to a λ at the operating frequency. As expected, the gain of a λ/2 wire dipole is also increased to 5.682 dB with the second AMC design. It is better than the AMC-1 design because the AMC-2 has a square-type and therefore produces better directional radiation pattern as can be seen in Figure 8(b) although it has a smaller AMC bandwidth.



(a)



(b)

Figure 8: Farfield of a half-wave wire dipole on (a) 17x4 unit cell AMC-1 (b) 6x6 unit cell AMC-2 at 2.45 GHz

Table 1
Summary of proposed AMC designs

	AMC-1	AMC-2
Size of one unit cell (mm)	30 x 7	18.3 x 18.3
Overall unit cell	17 x 4	6 x 6
Substrate material	RO3003	RO3010
Thickness of substrate (mm)	1.52	1.28
Relative permittivity of the substrate	3.0	10.2
Bandwidth	2.37 – 2.54 GHz (7%)	2.4 – 2.51 GHz (4.63%)
Gain (dB)	5.273	5.682

V. CONCLUSION

The issue of energy harvesting is a rising issue that draws many attentions of researchers in making this technique more reliable to be applied in numerous applications wirelessly. RF energy harvesting architecture comprises a rectenna in which included a receiving antenna, a matching circuit as well as a rectifying circuit as a RF-DC converter, and also a load at the end of the system layout. To make the rectenna more reliable, the antenna ought to be high-efficient antenna. Realizing this, number of study had been conducted to design the most optimized AMC. Then the antenna was attached with an AMC as a ground plane for the antenna in order to enhance the antenna performance in terms of gain and efficiency which is prove through past literature study. In this study, a new AMC structure was introduced centering at $2.45\ GHz$ for energy harvesting application. The numerical results demonstrated that this AMC fit, with theoretical characteristics of an AMC by having reflection phase at 0° which fall onto its $2.45\ GHz$ desired frequency plus a very high surface impedance of $\geq 1000\Omega$ at the same point. The working of AMC with λ/2 wire dipole antenna is tested computationally and it is shown that the gain of the antenna can be enhanced significantly. Moreover, in order to get a higher gain the square-type AMC is suggested, compared to the rectangular-type AMC.

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