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RADIO FREQUENCY (RF) ENERGY HARVESTING USING METAMATERIAL STRUCTURE FOR ANTENNA/RECTENNA COMMUNICATION NETWORK: A REVIEW

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ABSTRACT

Starting from the year 2000, metamaterial structure has been one of the favorite techniques used by several researchers to improve the performance of many radio frequency (RF) device designs, especially in the microwave range area. Wireless charging technologies that have emerged are also one of the highlighted discussions among users, fabricators and researchers. This paper presents a literature review of radio frequency energy harvesting, using a split ring resonator (SRR) and other metamaterial structure in antenna network applications. The objective of this paper is to define and compare the several performances such as the technique used, the material of the substrate, dimension, return loss and the resonant frequency of the antenna. The split ring resonator is an interesting metamaterial structure, that is applied in several researcher's work compared with other metamaterial structure such as electronic band gap (EBG), photonic band gap (PBG), and artificial magnetic conductor (AMC). This structure has the capability to improve the performance of the resonant frequency, minimizing the size and improving the return loss of the design, while sometimes creating a filter notch to the design. SRR structure is a good candidate for energy harvesting because it can increase the conversion efficiency.

Keywords: *Radio Frequency, Energy Harvesting, Antenna Network, Split Ring Resonator, Metamaterial, Rectenna*

1. INTRODUCTION

Urgent need caused by environmental conditions which are less secure and energy consuming to have caused widespread contamination in need of alternative energy such as energy harvesting from natural energy. Energy harvesting or energy scavenging is a practice where natural energy is derived from external sources that is caught and stored in small wireless devices.

The examples of energy harvesting sources are mechanical energy, thermal energy (heat), vibration, movement, sound, light energy, electromagnetic energy, natural energy, human body energy and others [1]. One of the advantages of energy harvesting is firstly, to improve the efficiency of the devices or the system. Secondly, to enable the implementation of a new technology, for example wireless sensor networks while the third is to reduce the cost of fabrication, for example the computing cost which can be reduced by harvesting the waste heat and this can be used to power the computer.

Previously, several reviews on energy harvesting has been carried out. Babayo [2] reviewed on the energy management scheme, in energy harvesting wireless sensor networks while Guo [3] focused on the piezoelectric and thermoelectric technologies for energy harvesting. In another review paper, Mohrehkesh [4] described energy harvesting in electromagnetic nanonetwork areas while Zhao [5], Invernizzi [6] and Albrni [7] focused on wind energy harvesting, the technique of energy harvesting on human motion and ultra-low power energy harvester wireless communication devices, respectively. Apart from that, Shaikh [8] reviewed wireless sensor networks while Soyata [9], Qasem [10] and Monticone [11] reviewed the RF energy harvesting in embedded system, rectenna design in energy harvesting, and metamaterial on the optical range, respectively. Sothman [12] focused on thermoelectric energy harvesting while Le [13] and Sum [14] focused on energy harvesting in aeronautical applications and metaresonator array on energy harvesting.

Radio Frequency (RF) energy harvesting is an emerging technology that will drive the next generation of wireless sensor networks (WSN) without the need of batteries. The battery is the main source of goods, but the disposal of it is causing extreme toxic pollution to the environment. In addition, the replacement and disposal of the battery are a hassle, because of its limited useful life [15]. Therefore, environmentally friendly technology is needed to avoid disposal of batteries that contain hazardous chemicals and metals.

RF energy harvesting is a green technology that has the potential to provide power indefinitely. It is suitable for an inclusive range of wireless applications, such as RFID tags, wireless sensor networks and implantable electronics devices. Figure 1 shows the block diagram of an effective antenna including a circuit capable of converting RF signals to DC voltage.

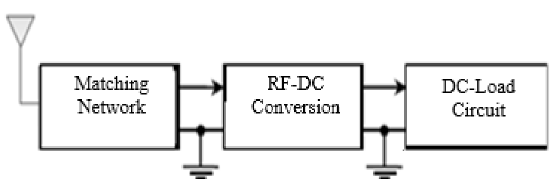

Figure 1: Block diagram of an effective antenna network alongside a circuit capable of converting RF signals to DC voltage.

The efficiency of an antenna mainly depends on its impedance and the impedance of the energy converting circuit [16-17]. A normal RF energy harvesting system consists of an antenna as the main component with an impedance matching circuit, voltage booster rectifier and a charging circuit.

The discussion of this study will focus on previous literature findings on several applications, such as antenna and rectifier antenna (rectenna) which apply the metamaterial structure like split ring resonator (SRR), electronic band gap (EBG), photonic band gap (PBG), and artificial magnetic conductor (AMC) for energy harvester.

Firstly, the focus is about the limitations of the previous antenna design works which only considered the patch antenna works, without other antenna such as the YagiUda, helical, horn antenna or parabolic type antenna. Secondly, the selected antenna of the previous study is only on the patch antenna with metamaterial structure such as SRR, EBG, PBG and AMC that is applied in the energy harvesting works. Also, the limit consideration of antenna is only focused on the microwave range antenna with antenna resonant frequency between 300 MHz and 300 GHz. It also focusses on the antenna or rectenna that with embedded structure of metamaterial.

The research gap of this work is that there are limited literature review papers which focus on the energy harvesting devices that apply the metamaterial structure in the antenna design. The previous research. The need of this research is to collect and describe the previous work about the metamaterials, which applied several works of the energy harvesting. The review of this study can be used for other researchers and show meaningful gaps in this topic. This collected literature review can be used to other researcher to compare and guide their next research. The limitation and demerits in this work is when searching for information including not open access manuscript in several libraries.

Again, this study of literature review will compare the several types of the metamaterial structure used in antenna or rectenna application. It also shows the material of the substrate used for fabrication, the resonant frequency used, antenna gain result and return loss achieved.

2. BASIC CONCEPT OF METAMATERIAL STRUCTURE

The metamaterial resonator structure has an artificial media that is not usually found in nature, but their parameters can be engineered to any specified value. Research on metamaterial resonator structure started in the late 1960s by Veselago [18] who introduced the electrodynamics of substances with simultaneously negative values of dielectric permittivity and magnetic permeability. Split ring resonator (SRR) is a popular and basic metamaterial resonator structure. Veselago explained that, if a material had both negative values (the magnetic and the electric response functions), i.e. ε - and μ -, the index of refraction would show a negative, n-. In the year 2000, the real design of the metamaterial structure was made by Smith [19], although a year before, the test was conducted by Pendry [20-21], who presented the split ring resonator structure, but it was not fabricate it that year.

Other types of metamaterial structure are the electronic band gap (EBG), photonic band gap (PBG), and artificial magnetic conductor (AMC). Other than SRR, the EBG structure is also becoming a rapidly advancing research area, in the field of the electromagnetic study. This EBG structure basically affects the ground plane to be like a perfect magnetic conductor.

In the microwave area range, the SRR structure is popular and can be found in many devices, such as antenna [22], RF oscillator [23], microwave filter [24], microwave absorber [25], RF amplifier [26], and frequency selective surface (FSS) [27].

One of the benefits of SRR and other metamaterial resonator structures, is the small unit cell structure with wide frequencies in order for radio frequency to be visible. The split ring resonator affects the improvement of coupling between the individual rings, while it can also reduce the electrical size [28]. In addition, [29] supported that the decrease of electrical size in split ring resonators can boost the coupling between the ring structures. Almoneef [30] discussed in his findings that, the SRR is viable for electromagnetic energy harvesting. In his experiment, a 9 x 9 SRR array with 3 x 3 microstrip patch antenna array was designed using numerical simulations. After the experiment was done, it was found that, the SRR array had a larger power collection compared to the microstrip patch alone.

The basic structure of the split ring resonator SRR, namely the edge couple SRR (EC-SRR), is shown in Figure 2. This structure consists of two similarly shaped couples with different dimensions of split rings. The rings create a strong distributed capacitance in between their region [31]. The other types of SRR structures are broadside couple SRR (BC-SRR) that consists of a single ring with a gap above and side of it [32], while a nonbianistropic couple (NC-SRR) is a uniplanar design of SRR to avoid the bianistropy effect in the EC-SRR bianistropy in the EC-SRR.

The SRR functions as a magnetic field, for the electromagnetic radiation to be driven as a resonant LC circuit through the inductance. The induced currents flow in the directions indicated, with charges assembling at the gaps of the rings. The large gap in each ring avoids the current from floating around in a single ring, and the circuit is completed across the small capacitive gap between the two rings [33]. In a different study, Palazzi [34] introduced a wireless energy harvesting rectenna with a broadband slot antenna for commercial telephony frequencies in the UHF band. The antenna design is based on an annular slot with an intersection of two ellipses and the slot aperture. The rectenna conversion efficiency was more than 60 %.

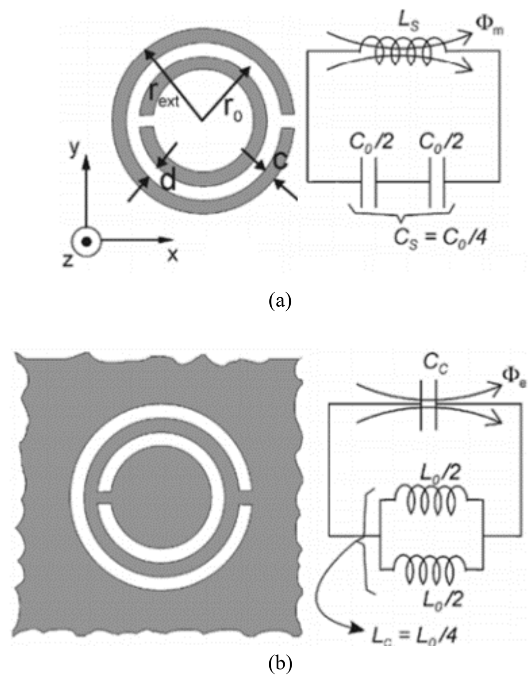

Figure 2: (a) Basic SRR structure, (b) Complementary SRR structure [35-36]

3. WORKS USING METAMATERIAL STRUCTURE

The above finding is consistent with a later study by Ashoor [37], that proposed a design of electromagnetic energy harvesting using small 1×3 elements of a dielectric resonator antenna (DRA) array. This DRA array structure was considered an outstanding radiator because it had a negligible metallic loss of its main radiator and the dielectric resonator (DR), as there were no metallic losses associated with DRAs. His finding showed that, the dielectric resonator has the highest absorption efficiency when compared with 1 x 3 dielectric resonator with d = n mm inter-element spacing (n = λ/2, λ/4, λ/5, λ/10 mm). Also, Jung [38] proposed a novel RF energy harvesting antenna with a main radiator and a parasitic radiator in the design. This parasitic radiator contained a two-turn loop structure that generally receives the RF power radiated at the outside of the 3-dB beam width of

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the main radiator. This parasitic radiator did not have any effect on the electrical performance of the main radiator, because DC power can be generated by the dissipated RF energy. Finally, the gain was 8.35 dBi, which was nearly like the printed dipole without the parasitic radiator performance.

Table 1: Summary of the several types of metamaterial structure at its microwave applications

Author	Application	Types of metamaterial	Material used	Frequency range	Remarks
Wang [42]	electrically small antenna (ESA)	SRR	FR4	at 934 MHz and 1.55 GHz	Reduce size by SRR
Ong, 2015 [43]	Wideband monopole antenna	SRR	FR4 epoxy board	Wideband 4.61 GHz to 10.23 GHz.	20 mm x 25 mm
Abu, 2016 [50]	Patch array antenna	AMC	RT 5880	Bandwidth between 66.68 GHz - 71.56 GHz	For millimetre wave
Alahnomi, 2016 [51]	microwave sensors	symmetrical SSR	Roger RT / Duroid 5880	2.30 GHz, 4.58 GHz, 6.86 GHz, 9.12 GHz	a high Q-factor with small insertion loss
Nikfalazar, 2012 [52]	Tuneable planer filter	SRR	Barium-Strontium-Titanate (BST) thick film ceramic	Passband frequency 2.8 GHz to 3.1 GHz	14 mm × 3 mm
Ezanuddin, 2011 [53]	Circular microstrip antenna	Circularly SRR	Rogers RT / D 5880	5.85 GHz - 7.075 GHz, resonant frequency of 6.438 GHz	Using for High Altitude Platform Station (HAPS)
Silva, 2016 [54]	microstrip patch antenna	EBG - PBG	RT / Duroid 6006	5.8 GHz with – 32 dB return loss	Gain 6.4 dB
Hamidkhani, 2016 [55]	low phase noise oscillators and diplexers	Complementary SRR	Rogers RT / Duroid 5880	oscillation frequency 5.36 GHz,	−128 dBc/Hz phase noise at 100 KHz frequency
Aznabet, 2011 [56]	metasurface	stacked SRR	ARLON CuClad 25	8.66 GHz, 11.49 GHz, 17.03 GHz, 18.73 GHz	200 mm × 200 mm (25 × 25 elements)
Bilotti, 2006 [57]	SRR microwave absorber	SRR	Not stated	Resonant frequency at 2 GHz	thickness of λ/20 (i.e., 7.5 mm)
Li, 2009 [58]	Microstrip bandpass filter	Complementary SRR	dielectric constant 2.65	centred at 1.93 GHz	insertion loss 1.7 dB
Huang, 2013 [59]	Substrate integrated waveguide filters	broadside-coupled SRR	Rogers 4350	Type III - 5.73 to 9 GHz	stopband rejection better than 20 dB.
Zuffanelli, 2017 [60]	UHF-RFID passive tags	Complementary SRR	Rogers RO3010	f_0 = 923 MHz	distance operate reaches 6.8 m
Mantash, [61]	wearable antenna	AMC	textile materials	2.4 GHz to 2.69 GHz, 5.15 GHz to 5.875 GHz	Cover WiFi and 4G LTE frequency bands
Sanz-Izquierdo, 2016, [62]	frequency selective surface	AMC	Rogers 5870	1.15 GHz - 1.60 GHz	FSS to reconfigurable antenna technology

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Liu [39] proposed a new system of cooperative cognitive radio network (CRN) with capabilities in harvesting energy. This network consists of N single-antenna secondary users (SU), one control centre with multi-antennas and one primary user (PU). Each secondary user harvests energy to power its uplink information transmission and spectrum sensing. Maher [40], also introduced a broadband planar antenna with a semi-circular patch fed as radiator and four stubs in the bottom part for radio frequency (RF) energy harvesting. The antenna had shown a high gain and good radiation pattern, with a broadband between 2.1 GHz to 7 GHz range and resonant frequencies of 2.4 GHz, 3 GHz, 4.1 GHz, and 5.8 GHz, acceptable for RF energy harvesting condition. Table 1 shows several types of metamaterial structure at its microwave applications.

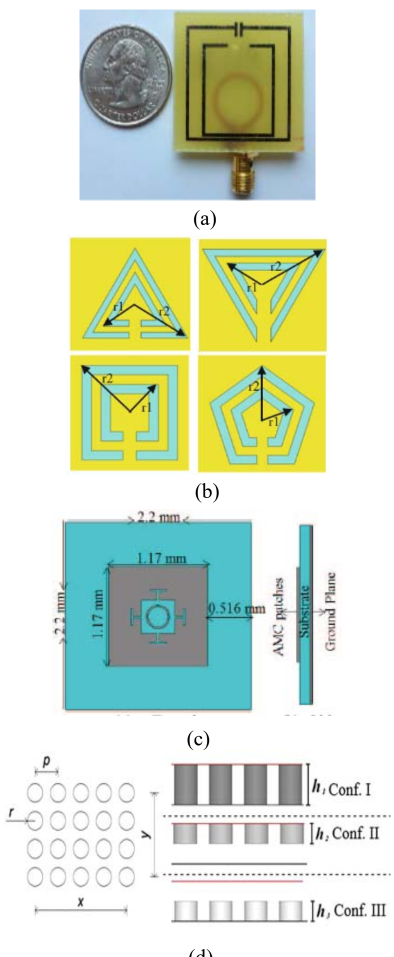

Figure 3: Examples of metamaterial structure on several devices, (a) Dual-band antenna with capacitive SRR [42], (b) Triangular SRR (point up), triangular SRR (point down), square SRR and pentagonal SRR [43], (c) AMC unit cell, (d) EBG/PBG structure for patch antenna design

In 2016, Khan [41] presented a design and the implementation of a novel of highly efficient UHF folded dipole meandering antenna, with a grounded parasitic loop and associated circuitry for energy harvesting at 915 MHz. The antenna was implemented on FR4 board with a dimension of 41.3 mm X 17.5 mm. The conversion efficiency of the harvesting circuit was measured to be 0.005% at a distance of 1.5m from the radiation source. In the test, a commercial UHF RFID reader was used as the radiation source. According to his findings, the implemented system could harvest around 200 µW at an optimal distance of 1.5 m, with the peak value of 647 µW at a distance of 0.5m from the radiation source. The split ring resonator structure was applied in many designs of radio frequency range and presented in several researches [44-49].

All these designs showed the improvement or the enhancement of performance that affects the result. In this table, several applications were added by the metamaterial structure, such as the antenna, planar filter, low phase noise oscillator, Diplexers and microwave absorber. In summary, metamaterial such as split ring resonator, photonic band gap, artificial magnetic conductor, and electromagnetic band gap have affected the different parameters of performance for each type of application in the RF range. Figure 3 shows the examples of metamaterial structure on several devices.

4. ENERGY HARVESTING ANTENNA/ RECTENNA WITH METAMATERIAL

Energy harvesting antenna or rectifier antenna (rectenna) is an interesting topic in the research field right now, because many researchers are focusing on this subject. Nowadays, the microwave rectenna systems have been fabricated to function in the range of frequencies between 1 GHz and 35 GHz. A rectenna is a sub-system of a wireless power transfer system (WPT). In the normal circuit using components such as antenna and rectifier, the incoming signal that will be received is from free space caught by the antenna. In 1968, Glasser introduced a rectenna as an energy harvesting medium, called the Space Solar Power which converted solar energy into electricity [63]. After that, the process continued with a pre-rectification filter before being sent to a diode and a post rectification. This is the filter cut off the unwanted spectrum and unwanted harmonics. In the energy harvesting system, the important component of the receiver part is the rectifier-antenna or rectenna. This rectenna receives the electromagnetic power from corresponding

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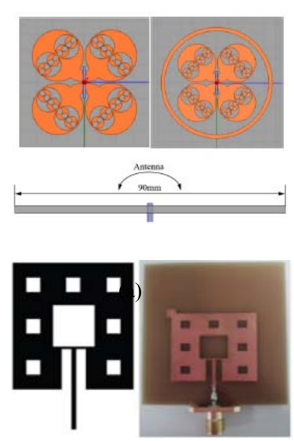
frequencies. A typical rectenna system contains a microstrip antenna to capture the microwave energy and convert into AC power and a high frequency rectifying circuitry, that converts the AC power into DC power. Figure 4 presents the block diagram of transmitting antenna and receiving antenna via a travelling medium or free space.

Figure 4: Block diagram of transmitting antenna and receiving antenna network

Assimonis [64] designed a low-cost lossy substrate and low-complexity rectenna grid that contain matching network and DC converter part. The design highly affected the efficiency of low-power input and captured as much power as possible that is offered at the load. A lossy substrate is used to reduce the cost of fabrication while the increased efficiency is affected by the additional of a single series circuit with a single diode. Two 868 MHz frequency bow-tie antennas are located between the rectifiers. Cao [65], introduced the CSRR-Fed SIW cavity-backed fractal patch antenna. The multi-band frequency difficulty requires that, any energy harvesting device should be well matched with all the frequency bands of the application available on site. This matter usually can be explained over the use of multi-band antennas, which has been broadly studied by other researchers [66]. An example of antenna for energy harvesting, is the novel efficient 3-D multi-frequency antenna that operates in five different frequency bands of GSM 1800MHz, UMTS 2100MHz, WLAN 2.4GHz, and WLAN 5.2GHz and WLAN 5.8 GHz. This small antenna is fabricated for the reception of ambient RF energy from a cellular network frequency [67]. Agrawal in 2013, introduced a compact sized 2.4 GHz antenna with an array J-cross-sectional reactive impedance surface (RIS) metamaterial structure of the circular slotted truncated corner square patch (CSTCSP).

Kamoda [69] carried out a research on the loop antennas over artificial magnetic conductor (AMC) surfaces for dual-band RF energy harvesting antenna. AMC is another type of metamaterial besides the SRR structure. His parametric study showed that the AMC surface with metal posts has a different frequency range compared with no metal posts. This design contains the energy harvesting panel with the antenna substrate, polystyrene as a spacer, rectifier circuit, power management circuit and ground plane using aluminium. Figure 5 shows Zhou [70] work which indicated as follows: (a) designed a multi-band fractal antenna for RF energy harvesting WLAN in 2.4 GHz and 5.8 GHz frequencies with a wider bandwidth between 1.6 GHz and 3.2GHz for the first resonant frequency and (b) between 4.88 GHz and 6.68 GHz for the second resonant frequency.

Moreover, Shrestha [71] had fabricated a miniaturised dual band patch antenna using Sierpinski fractal for radio frequency energy harvesting. In his design as shown in Figure 5, (b) a miniaturised antenna was operable at two different resonant frequencies of 2.45 GHz and 5.8 GHz. This antenna was constructed by modifying the standard microstrip patch antenna geometry into a Sierpinski fractal structure. His proposed antenna can also potentially remove unwanted harmonics without the use of additional radio frequency filter components. Again, Zhou [72] introduced a multiband antenna for energy harvesting using plasmonic metamaterial. A corrugated ring resonator was printed on a thin dielectric substrate of Roger RO4350 with a spiral-shaped defect ground structure (DGS) at the ground plane. On the other side, there was a T-shaped design with a periodic array of rectangular-shaped grooves. The presence of this DGS structure, formed more resonant frequencies. This structure also shifted the resonant frequencies into a lower point. Although, Devi [73] had proposed C-shaped antenna with the SRR array structure, he had designed a 5 x 5 metamaterial array split ring resonator at the patch antenna to resonate at 900 MHz with the improvement of the return loss and impedance bandwidth and gained 19.0 % (increase 6.71 dB), 23.33%, and 44.4% respectively.



(b)

Figure 5: Previous research on antenna/rectenna design with metamaterial structures, (a) multi-band fractal antenna for RF energy harvesting [70], (b) Miniaturized dual band patch antenna using Sierpinski [71].

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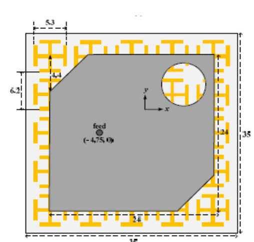
Another study was carried out by Jalil [74], where he proposed an octagon-shaped radiator fed microstrip antenna with matching ultra-wideband impedance and partial grounded substrate. This antenna was designed on Taconic TLC-30 substrate and operated as an ultra-wideband region between 2.8 GHz and 11 GHz with the band notch between 3.3 GHz to 3.6 GHz (WiMAX frequency operating band) from the inverted U-shaped slot at the patch. The novel receiving dual band geometry antenna for 2.45 GHz and 5 GHz by Bakkali [75] is another example of antenna for RF energy harvesting. Table 2 shows the summary of the several researches on metamaterial structure that is used in antenna / rectenna for energy harvesting.

Table 2: Summary of the several researches on metamaterial structure that used in antenna / rectenna for energy harvesting

Author, year	Technique used	Material used	Dimension size	Resonant frequency (GHz), Return loss (dB)	Gain (dB)
Cao, 2015 [65]	CSRR-Fed SIW cavity-backed fractal	F4B	40 mm x 40 mm	3.9 GHz 4.3GHz	4.6 dB 5.9 dB
Agarwal [68]	reactive impedance surface (RIS) metamaterial, circular polarized (CP)	dual-layer FR4 substrate	35 mm x 35 mm x 3.7 mm	2.44 GHz with better than – 35 dB	4.6 dB
Zhou, 2015 [72]	Spiral defected ground structure (DGS) metamaterial, T-shaped groove structure at patch	Rogers RO4350	60 mm x 60 mm	0.91 GHz, 1.79GHz, 2.53GHz	Directivity 1.71dBi, 5.69 dBi, 5.78 dBi
Devi, 2014 [73]	SRR metamaterial, stepped rectangular patch, air gap	Three layers FR4 substrate	74.4 mm x 49.9 mm	1.846 GHz, - 27.7 dB	-
Xu, 2016 [79]	SRR arc-shaped slot, 2×2 array, air gap	FR4	24.7 mm x 15 mm	1.89 GHz 2.05 GHz	5.3 dB 6.6 dB
Fhafhiem, 2016 [83]	Mushroom like electromagnetic band gap (EBG), partially reflective surface (PRS), air gap	Dual layer FR4	120 mm x 120 mm	2.45 GHz with > 10 dB	-10.05 dB
Shen [84]	anisotropic zero-index metamaterial (ZIM), Vivaldi antenna shaped	F4B	125 mm x 210 mm	2.45 GHz with > 10 dB	1.2 dB

The proposed receiving antenna achieved the essential bandwidth specification and delivered a peak gain of more than 4 dBi across the operating frequency bands. Besides, there are many antennas designs for RF energy harvesting such as MIMO relay by Samy [76], RF energy harvester antenna by Ramesh [77], RF energy harvesting rectenna by Abdullah [78], dual broadband antenna array for RF energy harvesting by Xu [79], bow-tie antenna using SRR for energy harvesting by AlShareef [80], antenna with circular polarization for energy harvesting by Ahmed [81], and compact tree-shaped coplanar waveguide (CPW) antenna for RF energy harvesting by Zakaria [82]. Fhafhiem also designed a patch microstrip and EBG including PRS superstrate [83]. Figure 6 shows another work on antenna with metamaterial structures.


(a)

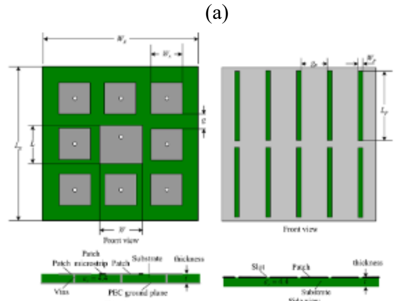

(b)

Figure 6: (a) RIS based antenna design [68], (b) Patch antenna with EBG and PRS superstrate

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5. RF ENERGY HARVESTING SYSTEM NETWOKS

Figure 7 shows the RF energy harvesting system networks by [68]. In this case, a single stage Dickson charge pump was applied as a rectifier and as a voltage multiplier circuit. The miniaturized size circularly polarized microstrip antennas (CPMAs) with metamaterial reactive impedance surface RIS structure and charger chip BQ25504, which had been installed as part of the complete system. This antenna has the capacity to boost the antenna gain and improve the bandwidth, which functions the energy harvesting system. This proposed antenna includes, the whole CP frequency range of 2.40 GHz to 2.48 GHz with a size reduction of approximately 22% and increase the efficiency of the system to 28.9 %.

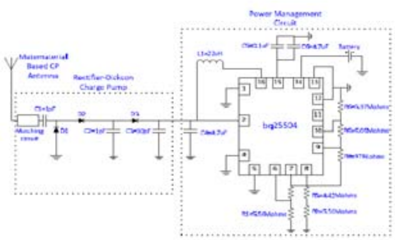

Figure 7: Proposed RF energy harvesting system networks with circularly polarized microstrip antennas (CPMAs).

After the review on the application of the rectenna and the antenna for energy harvesting, it shows that there are many design works that applied the SRR structure, but limited work is done on the other metamaterial structure like SRR, EBG, PBG and AMC structure. This is because, the SRR structure is easier to design compared with the others and hasthe capability to miniaturize the size of the antenna. Besides that, this structure also has the potentials to create a multiband frequency effect to the antenna. Among the gaps that can be reduced by future researchers is by applying the others structure in their design. Their research can be combined with several types of metamaterials in one antenna, in order to see the performance effect of the antenna. Improvement work can be done, by using other material substrate to increase the performance of the antenna.

7. CONCLUSION

Metamaterial such as the SRR, AMC, PBG and EBG has the potential to improve the performances of the design in many RF applications. A five-year range of research showed that, there are many researchers who focused on this area by providing enhancement work on its efficiency and higher return loss performance. Based on the above review, it is summarized that there are several additional aspects to be considered when designing a good energy harvester device using several RF range applications, in comparison with a conventional basic RF application design. It can be concluded that the addition of the metamaterial structure had been improve the performance of the return loss or can effect to reduces the dimension of the antenna. The antenna with metamaterial for the energy harvesting area is a favorite subject, because in contemporary studies, there have been many researches covering the topic. It shows that, the antenna performance can be improved upon by adding the metamaterial structure. The significant improvement of the metamaterial antenna is that, it reduces the size, creates more resonant frequency for multi-application and creates the band-notch rejecting frequency.

The result of this review shows that, RF application that is incorporated with metamaterial can be successfully applied as energy harvesting devices in many designs, such as in the antenna and rectenna (antenna with rectifier). The addition of SRR and several structures of metamaterial to the antenna can reduce the size of the antenna and sometimes can be a notch band to filter certain ranges of frequency.

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REFRENCES:

[1] Tentzeris M. M., A. Georgiadis, L. Roselli, "A Energy Harvesting and Scavenging," *Proceedings of the IEEE*, 2014, 102, (11), pp. 1644 - 1648

[2] Babayo A. A., M. H. Anisi, I. Ali, "A Review on energy management schemes in energy harvesting wireless sensor networks,"

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

Renewable and Sustainable Energy Reviews, 2017, 76, pp. 1176 - 1184

[3] Guo L., Q. Lu, "Potentials of piezoelectric and thermoelectric technologies for harvesting energy from pavements," *Renewable and Sustainable Energy Reviews, 2017*, 72, pp. 761 - 773

[4] Mohrehkesh S., M. C. Weigle, S. K. Das, "Energy Harvesting in Electromagnetic Nanonetworks," *Computer,* 2017, 50, (2), pp. 59 - 97

[5] Zhao L., Y. Yang, "Toward Small-Scale Wind Energy Harvesting: Design, Enhancement, Performance Comparison, and Applicability," *Shock and Vibration*, 2017, pp. 1 - 31

[6] Invernizzi F., S. Dulio, M. Patrini, G. Guizzetti, P. Mustarelli, "Energy harvesting from human motion: Materials and techniques," *Chemical Society Reviews*, 2016, 45, (20), pp 5455 - 5473

[7] Albrni M. A., J Sampe, M. S. Islam, B. Y. Majlis, "Ultra low power energy harvester using hybrid input for wireless communication devices - A review," *Journal of Theoretical and Applied Information Technology*, 2016, 86, (3), pp. 365 - 376,

[8] Shaikh F. K., S. Zeadally, "Energy harvesting in wireless sensor networks: A comprehensive review," *Renewable and Sustainable Energy Reviews,* 2016, 55, pp. 1041 - 1054

[9] Soyata T., L. Copeland, W. Heinzelman, "RF Energy Harvesting for Embedded Systems: A Survey of Tradeoffs and Methodology,*" IEEE Circuits and Systems Magazine,* 2016,16, (1), pp. 22 - 57,

[10] Ahmed Qasem S., M. N., Husain, Z. Zakaria, M.S.I.M. Zin, A. Alhegazi, "Rectenna designs for RF energy harvesting system: A review," *International Journal on Communications Antenna and Propagation*, 2016, 6, (2), pp. 82 - 89

[11]Monticone F. and A. Alù, "Metamaterial, plasmonic and nanophotonic devices,*" Reports on Progress in Physics*, 2017, 80, (3), pp. 1 - 37

[12] Sothmann B., R. Sanchez, A. N. Jordan, "Thermoelectric energy harvesting with quantum dots," *Nanotechnology*, 2015, 26, (3), pp. 1 - 46

[13] Le, M. Q., J.-F. Capsal, M. Lallart, Y. Hebrard, A. Van Der Ham, N. Reffe, L. Geynet, P.-J. Cottinet, "Review on energy harvesting for structural health monitoring in aeronautical applications," *Progress in Aerospace Sciences*, 2015, 79, pp. 147 - 157

[14] Sum Y. L, B. H. Song, K. J. Tseng, "Selection of unit cell size for RF energy harvesting metaresonator array," *5th IET International Conference on Renewable Power Generation*, 2016, pp. 1-6

[15] Chen Z., B. Guo, Y. Yang, C. Cheng, "Metamaterials-based enhanced energy harvesting: A review", *Physica B: Condensed Matter*, vol. 438, pp. 1 - 8, 2014

[16] Devi K. K. A., N. C. Hau, C. K. Chakrabarty, N. M. Din, "Design of Patch Antenna Using Metamaterial at GSM 1800 for RF Energy Scavenging," *2014 IEEE Asia Pacific Conference on Wireless and Mobile*, pp. 157 - 161, 2014

[17] Devi K. K. A., S. Sadasivam, N. M. Din, C. K. Chakrabarthy, "Design of a 377 Ω Patch Antenna for Ambient RF Energy Harvesting at Downlink Frequency of GSM 900," *The 17th Asia Pacific Conference on Communications*, pp. 492 - 495, 2011

[18] Veselago, V., "The Electrodynamics of Substances with Simultaneously Negative Values of ε and μ," *Soviet Physics Uspekhi*, 1968, 10, (4), pp. 509 – 514,

[19] Smith, D. R., Padilla, W. J., Vier, D. C., Nemat-Nasser, S. C., and Schultz, S., "Composite Medium with Simultaneously Negative Permeability and Permittivity," *Physics Review Letter*, 2000, 84, pp. 4184 – 4187

[20] Pendry, J. B., Holden, A. J., Robins, D. J., and W. J. Stewart, "Magnetism from Conductors and Enhanced Nonlinear Phenomena," *IEEE Transactions on Microwave Theory and Techniques*, 1999, 47, (11), pp. 2075 – 2084,

[21] Pendry, J. B., "New Lenses for Imaging the Near Field," *Postconference Digest Quantum Electronics and Laser Science (QELS)*, 2003, pp. 1 – 2

[22] Zarrabi, F. B., S. Sharma, Z. Mansouri, F. Geran, "Triple Band Microstrip Slot Antenna for WIMAX/WLAN Applications with SRR Shape Ring," *2014 Fourth International Conference on Advanced Computing & Communication Technologies (ACCT),* 2014, pp. 368 – 371

[23] Choi, J., C. Seo, "Broadband VCO using Electronically Controlled Metamaterial Transmission Line Based on Varactor-Loaded Split-Ring Resonator," *Microwave and Optical Technology Letters,* 2008, 50, (4), pp. 1078 – 1082

[24] Mahyuddin, N. M., N. F. S., Kadir Ab., "Design of a 5.8 GHz Bandstop Filter Using

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

Split Ring Resonator Array," The 8th International Conference on Robotic, Vision, Signal Processing & Power Applications *Lecture Notes in Electrical Engineering*, 2014, 291, pp. 473 – 482

[25] Bilotti, F., A. Toscano, A. K. Boratay, E. Ozbay, L. Vegni, "Design of Miniaturized Narrowband Absorbers Based on Resonant-Magnetic Inclusions," *IEEE Transactions on Electromagnetic Compatibility*, 2011, 53, (1), pp. 63 – 72

[26] Chen, L., J. Li., H. Pan., X. Q. Yi, "An Efficiency-Improved Power Amplifier using Split-Ring Resonator Defected Ground Structure," *2010 Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC)*, 2010, pp. 1421 – 1423

[27] Ortiz, J. D., J. D. Baena, V. Losada, F. Medina, and J. L. Araque, "Spatial Angular Filtering by FSSs Made of Chains of Interconnected SRRs and CSRRs," *IEEE Microwave and Wireless Components Letters*, 2013, 23, (9), pp. 477 – 479,

[28] Aznar, F., Bonache, J., Martin, F., Ozbay, E., Alici, K. B., Bilotti, F., Tricarico, S., Vegni, L., Baena, J. D., Jelinek, L., Marques, R., "Miniaturization and Characterization of Metamaterial Resonant Particles," *38th European Microwave Conference (EuMC 2008)*, 2008, pp. 269 – 272

[29] García-García, J., Bonache, J., Gil, I., Martín, F., Ahumada, M. del C.V. and Martel, J., "Miniaturized Microstrip and CPW Filters Using Coupled Metamaterial Resonators," *IEEE Transactions on Microwave Theory and Techniques*, 2006, 54, (6), pp. 2628 – 2635,

[30] Almoneef T. S., O. M. Ramahi, "Can Split-Ring Resonators be viable for electromagnetic energy harvesting?" *IEEE Antennas and Propagation Society, AP-S International Symposium (Digest)*, pp. 424 - 425, 2014

[31] Marques, R., J. D. Baena, J. Martel, F. Medina, F. Falcone, M. Sorolla, and F. Martin, "Novel Small Resonant Electromagnetic Particles for Metamaterial and Filter Design," *International Conference on Electromagnetics in Advanced Applications (ICEAA)*, 2003, pp. 439 – 442

[32] Marques, R., F. Mesa, J. Martel, F. Medina, "Comparative Analysis of Edge - and Broadside - Coupled Split Ring Resonators for Metamaterial Design - Theory and Experiments," *IEEE Transactions on Antennas and Propagation*, 2003, 51, (10), pp. 2572 – 2581

[33] Marques, R., R. Medina, E. I. Raffi, "Role of Bi-anistropy in Negative Permeability and Left-handed Metamaterials," *Physics Review B*, 2002, 65, pp. 144441

[34] Palazzi V., M. D. Prete, M. Fantuzzi, "Scavenging for Energy: A Rectenna Design for Wireless Energy Harvesting in UHF Mobile Telephony Bands," *IEEE Microwave Magazine*, 2017, 18, (1), pp. 91 - 99

[35] Baena J. D., J. Bonache, F. Martín, R. Marqués, F. Falcone, T. Lopetegi, M. A. G. Laso, J. García–García, M. F. Portillo, and M. Sorolla, "Equivalent-circuit Models for Split-ring Resonators and Complementary Split-ring Resonators Coupled to Planar Transmission Lines," *IEEE Transactions on Microwave Theory and Techniques*, 2005, 53, pp. 1451 – 1461

[36] Baena, J. D., Marques, R., Medina, F., and Martel, J., Artificial Magnetic Metamaterial Design by using Spiral Resonators, *Physics Review B*, 2004, 69, pp. 1 – 5

[37] Ashoor A. Z., O. M. Ramahi, "Electromagnetic Energy Harvesting Using Dielectric Resonator Antenna," *2016 IEEE International Symposium on Antennas and Propagation (APSURSI)*, 2016, pp. 151 - 152

[38] Jung Y.-B., Energy Harvesting Antenna for Various Communication Transceivers, *2014 IEEE MTT-S International Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-Bio2014)*, 2014, pp. 1-3

[39] Liu H., J. Chen, G. Ding, T. A. Tsiftsis, C, Rowell, "Antenna beamforming for energy harvesting in cognitive radio networks," *2016 IEEE MTT-S International Wireless Symposium (IWS)*, 2016, pp. 1 - 4

[40] Maher R., E. Tammam, A. I. Galal, H. F. Hamed, "Design of a Broadband Planar Antenna for RF Energy Harvesting," *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*, 2016, pp. 1808 – 1810

[41] Khan M. S., H. Deng, "Design and Implementation of a Highly Efficient UHF Energy Harvesting Antenna," *2016 IEEE International Symposium on Antennas and Propagation (APSURSI)*, 2016, 611 – 612

[42] Wang L. M. Q. Yuan, Q. H. Liu, "A dual-band printed electrically small antenna covered by two capacitive split-ring resonators," *IEEE Antennas and Wireless Propagation Letters*, 2011, (10), pp. 824 - 826

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

[43] Ong T. K., B. H. Ahmad, M. Z. A. Abd. Aziz, M. A. Othman, M. K. Suaidi, F. Abd. Malek, "Investigation of the Shape of SRR Slot and Hybrid Material on Wideband Monopole Antenna," *Theory and Applications of Applied Electromagnetics,* 2015, pp 321 - 328

[44] Gunduz, O. T., and Sabah, C., "A Novel Left-Handed Metamaterial Based on Circular Resonator and Wire Strip for Waveguide Applications," *2014 16th International Conference on Transparent Optical Networks (ICTON),* 2014, pp. 1 - 4,

[45] Perez, D., Gil, I., and Fernandez-Garcıa, R., "Radiofrequency Interferece Filters Design Based on Complementary Split Rings Resonators," *PIERS Proceedings*, 2012, pp. 818 – 822

[46] Kafesaki, M., Kenanakis, G., Economou, E. N., Soukoulis, C. M., "Chiral Metamaterials: A Tool for THz Polarization Control,". *2014 16th International Conference on Transparent Optical Networks (ICTON*), 2014, pp. 1 - 2,

[47] Jakovljević, M., Vasić B., Isić G., Gajić, R., Oates T., Hinrichs K., Bergmair I., Hingerl K., "Oblique Incidence Reflectometry and Spectroscopic Ellipsometry of Split-Ring Resonators in Infrared," *Journal of Nanophotonics, 2011*, 5, (1), pp. 051815 – 10,

[48] Maissen, C., Scalari, G., Valmorra, F., Cibella, S., Leoni, R., Reichl, C., Charpentier, C., Wegscheider, W., Beck, M., Faist, J., "Ultrastrong Coupling in the Near-field of Complementary Split Ring Resonators," *Mesoscale and Nanoscale Physics*, 2014, pp. 1 - 9

[49] Gil, I., Bonache, J., Gil, M., Garcia-Garcia, J., Martin, F., Marques, R., "Modelling Complementary-Split-Rings-Resonator (CSRR) Left-Handed Lines with Inter-Resonator's Coupling, 2006," *IEEE Mediterranean Electrotechnical Conference (MELECON 2006),* 2006, pp. 225 – 228

[50] M. Abu, M. Muhamad, Z. Zakaria, H. Hasan, "Millimeter-Wave *Parasitic AMC Patches on the Array Antenna," 2016 International Conference on Computer and Communication Engineering (ICCCE),* 2016, pp. 19-24,

[51] Alahnomi, R., Z. Zakaria, E. Ruslan, A. A. M. Bahar, "A Novel Symmetrical Split Ring Resonator Based on Microstrip for Microwave Sensors," *Measurement Science Review,* 2016, 16, (1), pp. 21 - 27

[52] Nikfalazar M., M. Sazegar, Y. Zheng, H. Maune, A. Mehmood, R. Jakoby, "Tunable split ring resonators (SRR) filter based on barium-strontium-titanate thick film," 2012 *The 7th German Microwave Conference,* 2012, pp. 1 – 4

[53] Ezanuddin A. A. M., M. F. Malek, P. J. Soh, "Preliminary Study of Circularly Split Ring Resonators Entrenched within Circular Microstrip Antenna," *International Journal of Engineering & Technology IJET-IJENS*, 2011, 11, (02), pp. 27 - 37

[54] da Silva J. L., H. D. de Andrade, A. S. Maia, H.C.C. Fernandes, I.B.T. da Silva, A.S.B. Sombra, J.P.P. Pereira, "Performance of microstrip patch antenna due EBG/PBG arrangements insertion," *Microwave and Optical Technology Letters, 2016,* 58, (12), pp. 2933 - 2937

[55] Hamidkhani M., F. Mohajeri, "Dual-Band Complementary Split-Ring Resonator (CSRR) with High-Quality Factor and Its Applications in Low Phase Noise Oscillators and Small Multi-Band Diplexers and Filters," *Progress in Electromagnetics Research M*, 2016, 52, pp. 33 – 44

[56] Aznabet M., M. Navarro-Cia, M. Beruete, F. J. Falcone, M. Sorolla Ayza, O. El Mrabet, and M. Essaaidi, "Transmission Properties of Stacked SRR Metasurfaces in Free Space," *Progress in Electromagnetics Research M*, 2011, 20, pp. 1 - 11

[57] Bilotti F., L. Nucci, L. Vegni, "An SRR based microwave absorber," *Microwave and Optical Technology Letters,* 2006, 48, (11), pp. 2171 – 2175

[58] Li, C., F. Li, "Microstrip bandpass filters based on zeroth-order resonators with complementary split ring resonators," *IET Microwaves, Antennas & Propagation*, 2009, 3, (2), pp. 276-280

[59] Huang, L., Robertson, I. D., W. Wu, N. Yuan, "Substrate integrated waveguide filters with broadside-coupled complementary split ring resonators," *IET Microwaves, Antennas & Propagation*, 2013, 7, (10), pp. 795 – 801

[60]Zuffanelli, S., G. Zamora, F. Paredes, FP. Aguila, F. Martin, J. Bonache, "On-metal UHF-RFID passive tags based on complementary split-ring resonators," *IET Microwaves, Antennas & Propagation,* 2017, 11, (7), pp. 1040 – 1044

[61] Mantash, M., Tarot, A. C., Collardey, S., Mahdjoubi, "Design methodology for wearable antenna on artificial magnetic conductor using stretch conductive fabric," *Electronics Letters*, 2016, 52, (2), pp. 95 – 96

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

[62] Sanz-Izquierdo, B., B. Liang, E. A. Parker, J. C. Batchelor, An application of active frequency selective surface to reconfigurable antenna technology, *Active and Passive RF Devices Seminar*, 2016, pp. 1-5

[63] Erb R. B., "Power from Space — The Tough Questions: The 1995 Peter E. Glaser Lecture," *Acta Astronautica*, 1996, 38, (4-8), pp. 539 - 550,

[64] Assimonis S. D., A. Bletsas, "Energy harvesting with a low-cost and high efficiency rectenna for low-power input," *2014 IEEE Radio and Wireless Symposium (RWS)*, 2014, pp. 229 - 231

[65] Cao H., Fen Jiang, Jiujiu Liu, Wenbin Cai, Mingchun Tang, Xiaoheng Tan, and Shizhong Yang, "A CSRR-Fed SIW Cavity-Backed Fractal Patch Antenna for Wireless Energy Harvesting and Communication," *Sensors*, 2015, 15, pp. 1196 - 1203

[66] Bui D. H. N., T. P. Vuong, P. Benech, J. Verdier, B. Allard, "Adjustable Frequency Antenna using Flexible Material for RF Energy Harvesting Application, *2016 IEEE International Symposium on Antennas and Propagation (APSURSI)*," 2016, pp. 615 - 616

[67] Bui D. H. N., T.-P. Vuong, J. Verdier, B. Allard, P. Benech, "3-D Multi-Frequency Antenna for RF Energy Harvesting Application," *2015 International Conference on Advanced Technologies for Communications (ATC)*, 2015, pp. 59 - 62,

[68] Agarwal K., T. Mishra, M. F. Karim, Nasimuddin; M. O. L. Chuen; Y. X. Guo, S. K. Panda, "Highly Efficient Wireless Energy Harvesting System using Metamaterial Based Compact CP Antenna," *2013 IEEE MTT-S International Microwave Symposium Digest (MTT)*, 2013, pp. 1 - 4

[69] Kamoda H., S. Kitazawa, N. Kukutsu, K. Kobayashi, Loop Antenna Over Artificial Magnetic Conductor Surface and Its Application to Dual-Band RF Energy Harvesting, *IEEE Transactions on Antennas and Propagation,* 2015, 63, (10), pp. 4408 - 4417

[70] Zhou Z., W. Liao, Q. Zhang, F. Han, Y. Chen, A Multi-Band Fractal Antenna for RF Energy Harvesting, *2016 IEEE International Symposium on Antennas and Propagation (APSURSI),* pp. 617 - 618, 2016

[71] Shrestha S., S. R. Lee, and D.-Y. Choi, "A New Fractal-Based Miniaturized Dual Band Patch Antenna for RF Energy Harvesting", *International Journal of Antennas and Propagation,* 2014, pp. 1 - 9

[72] Zhou Y. J., L. Yang, Q. X. Xiao, T. Y. Pan, H. F. Ma, C. Tan, "Plasmonic Metamaterials Based Subwavelength Multiband Antenna for Wireless Energy Harvesting," *2016 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP),* 2016, pp. 1 - 4,

[73] Devi, K. A., N. H. Ng, C. F. Kwong, C. K. Chakrabarty, N. M. Diah, "Investigations on Characteristics of Metamaterial Based Patch Antenna for RF Energy Harvesting at GSM 900." *Electrical and Electronic Engineering,* 2015, 5, (1A), pp. 7 - 13

[74] Jalil Y. E., B. Kasi and C. K. Chakrabarty, "A Compact Ultra-Wideband Antenna with WiMAX band Rejection for Energy Scavenging," *IOP Conference Series: Earth and Environmental Science,* 2013, 16, pp. 1 - 4

[75] Bakkali A., J. Pelegri-Sebastia, T. Sogorb, V. Llario, and A. Bou-Escriva, "A Dual-Band Antenna for RF Energy Harvesting Systems in Wireless Sensor Networks," *Journal of Sensors*, 2016, pp. 1 - 8

[76] Samy I., M. M. Butt, A. Mohamed, M. Guizani, "Energy Efficient Antenna Selection for a MIMO Relay using RF Energy Harvesting," *2016 IEEE Wireless Communications and Networking Conference*, 2016, pp. 1-6

[77] Ramesh G. P., A. Rajan, "Microstrip antenna designs for RF energy harvesting," 2014 *International Conference on Communication and Signal Processing*, 2014, pp. 1653 – 1657

[78] Abdullah N., A. M. Shire, E. Mohd, A. M. Shire, "Rectenna for RF energy harvesting," *2016 International Conference on Advances in Electrical, Electronic and Systems Engineering (ICAEES),* 2016, pp. 318 – 321

[79] Xu L.-J., B. Huang, X. Bai, H.-P. Mao, "A Dualband and Broadband Antenna Array for Ambient RF Energy Harvesting," *2016 IEEE International Conference on Ubiquitous Wireless Broadband (ICUWB)*, 2016, pp. 1 - 3

[80] AlShareef M. R., O. Ramahi, Energy harvesting in the microwaves spectrum using electrically small resonators, *1st International Congress on Energy Efficiency and Energy Related Materials (ENEFM 2013),* 2014, 155, pp. 265 - 272

[81] Ahmed S., Z. Zakaria, M. N. Husain, M. Abu, "Microstrip Antenna Design with Circular Polarization Property for RF Energy Harvesting application," *International Journal of Applied*

Engineering Research, 2016, 11, (6), pp. 4398 - 4401

[82] Zakaria Z., Zainuddin N. A., Husain M. N., M. Z. A. Abd Aziz, M. A. Mutalib, "Investigation of Compact Tree-Shaped Coplanar Waveguide (CPW) Antenna for RF Energy Harvesting," *Applied Mechanics & Materials*, 2014, 699, pp. 903 - 908

[83] Fhafhiem N., W. Naktong, E. Khoomwong, P. Krachodnok, "Design of resonator rectenna using metamaterials for wireless power transmission," *2016 13th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON 2016)*, 2016, pp. 1 - 4

[84] Shen J., J. Wen, X. Yang, X. Liu, H. Guo, C. Liu, D. Xie, "WLAN 2.4 GHz RF energy harvester using Vivaldi antenna loaded with ZIM," *Proceeding 2016 IEEE International Workshop on Electromagnetics (iWEM 2016)*, pp. 1 - 3, 2016