

METASURFACE COLLECTORS FOR AMBIENT RF ENERGY HARVESTING
APPLICATIONS

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To my beloved parents for their prayers and love, thank you.

To my brother, may his soul be embraced in the sacred bond of the eternal life and rest in peace

To my wife Belqes Amer and beloved kids, Alaa, and Mohammed, for their love and support.

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ABSTRACT

Metasurface is a planar type of metamaterial that is preferred in all electromagnetic applications due to its simplicity. Metasurfaces can be constructed using an array of electrically small resonators. This work investigates the feasibility of using small, highly efficient metasurface structures as RF collectors for energy harvesting applications. The first part of this work discussed a new metasurface split-ring resonator (SRR) absorber as an energy harvester. An array of 7x7 SRR metasurface resonators were designed and fabricated to maximise energy absorption at broadband frequencies of 1.88 GHz to 6.4 GHz. An air layer is placed between the dielectric substrate and the ground plane to enhance the absorption bandwidth. In addition, four resistor loads placed on the splits of the top metallic layer of the resonator are used to achieve a polarization-insensitive, wide-angle from 0° up to 60° , higher absorption, and higher harvesting efficiency. The near-unity absorption of over 90% and the harvesting efficiency of around 88% are achieved over a wider frequency range. Therefore, an efficient miniaturized wideband metasurface energy harvester is introduced in the second part of this work. A design of the electromagnetic metasurface harvester inspired by an array of printed metallic electric ring resonators (ERR) is presented. A finite array of 5x5 ERR unit cells is analysed numerically and experimentally at 5 GHz band. The array is analysed for maximising radiation to AC conversion efficiency where a resistor terminates each resonator through a metallic via. The overall radiation to AC harvesting efficiency of about 91% and 78% was obtained numerically at normal incidence and different oblique incidence angles up to 60° , respectively. Unlike earlier metasurface harvesters that connected each resonator to a load, this novel design uses a feed network to connect all resonators to one load to increase the efficiency. The novel proposed metasurface is based on the double-elliptical cylinder resonator that can capture energy at 5 GHz band. The simulation results yielded radiation to AC efficiency of 94% at normal incidence. A finite array of 4x4 unit cells was fabricated and tested experimentally for verification.

ABSTRAK

Permukaan meta merupakan salah satu kumpulan kecil dari planar bahan meta yang menjadi pilihan berbanding bahan meta di dalam bidang elektromagnet kerana rekabentuknya yang ringkas. Permukaan meta boleh dibina menggunakan pelbagai rekabentuk ulangan yang kecil. Maka, kajian ini menggunakan kelebihan permukaan meta untuk aplikasi penyerapan dan penuaian tenaga. Bahagian pertama kerja ini membincangkan penemuan baru bagi penyalun cincin berbelah menggunakan permukaan meta (SRR) dalam bentuk tatususunan sebagai penyerap tenaga. Tatususunan penyalun bersaiz 7x7 SRR telah direka bentuk bagi memaksimumkan penyerapan tenaga pada frekuensi jalur lebar 1.88 GHz hingga 6.4 GHz. Lapisan udara diletakkan di antara penebat substrat dan bahagian pembumian untuk meningkatkan lebar jalur penyerapan tersebut. Di samping itu, empat beban perintang yang diletakkan pada bahagian lapisan atas logam penyalun digunakan bagi meningkatkan kecekapan penyerapan polarisasi, sudut lebar dari 0° sehingga 60° , dan kadar penyerapan yang lebih tinggi. Penyerapan sebanyak 90% dapat dicapai bagi pelbagai sudut dan polarisasi yang berbeza. Maka, konsep menggunakan struktur permukaan meta elektromagnet bersaiz kecil sebagai penuai tenaga diperkenalkan pada bahagian kedua thesis ini. Reka bentuk permukaan meta penuai berdasarkan pelbagai penyalun cincin logam bercetak (ERR) telah dicipta. Susunan sel unit ERR 5x5 telah di analisa dengan menggunakan kaedah simulasi berangka dan eksperimen pada frekuensi 5 GHz. Malah, analisis susunan berulang telah di jalankan bagi memaksimakan kecekapan radiasi kepada penukaran ke arus ulang alik (AC), di mana perintang telah ditambah pada setiap logam penyalun permukaan meta tersebut. Penuaian tenaga sebanyak 91% bagi radiasi secara terus dan 80% telah di peroleh apabila arah radiasi di serongkan dengan pelbagai sudut sehingga 60° . Rekabentuk permukaan meta dari kajian sebelum ini menghubungkan setiap penyalun ke beban, tetapi, reka bentuk kajian ini menggunakan rangkaian suapan untuk menghubungkan semua penyalun ke satu beban. Ciptaan baru ini berdasarkan penyalun silinder elips silang yang dapat

menangkap tenaga pada frekuensi 5 GHz. Hasil keputusan simulasi menunjukkan kecekapan AC mencapai sebanyak 94% pada sudut radiasi secara terus. Bagi tujuan pengesahan keputusan kajian, susunan sel unit 4x4 telah di fabrikasi dan diuji secara eksperimen.



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LIST OF SYMBOLS AND ABBREVIATIONS

| | | |
|--------------------|---|------------------------------------|
| 2D | - | Two-Dimensional |
| 3D | - | Three-Dimensional |
| $\epsilon(\omega)$ | - | Permittivity |
| $\mu(\omega)$ | - | Permeability |
| $\Gamma(\omega)$ | - | Reflection |
| Ω | - | Ohm |
| λ | - | Wavelength |
| $A(\omega)$ | - | Absorption |
| AC | - | Alternative Current |
| BCR | - | Butterfly-Shaped Closed Resonator |
| CQSRR | - | Complementary Quad SRR |
| CSRR | - | Complementary Split Ring Resonator |
| CST | - | Computer Simulation Technology |
| dB | - | Decibels |
| DNG | - | Double-Negative |
| E | - | Electric Field |
| <i>EH</i> | - | Energy Harvesting |
| ELC | - | Electric Capacitive Resonator |
| EM | - | Electromagnetic |
| ERR | - | Electric Ring Resonator |
| <i>f</i> | - | Frequency |
| FIM | - | Finite Integral Method |
| G-CSRR | - | Ground Back SRR |
| G_T | - | Gain of Transmitter Antenna |
| G_R | - | Gain of Receiver Antenna |
| H | - | Magnetic Field |
| HPBW | - | Half Power Beam Width |

| | | |
|-------------|---|--------------------------------|
| IoT | - | Internet of Things |
| LHM | - | Left-Hand Media |
| P_{in} | - | Input power |
| P_{load} | - | Power Dissipated in The Load |
| P_R | - | Power Received |
| P_T | - | Power Transferred |
| R | - | Distance |
| RF | - | Radio Frequency |
| RFID | - | Radio Frequency Identification |
| SRR | - | Split Ring Resonator |
| $T(\omega)$ | - | Transmission |
| TEM | - | Transverse Electromagnetic |
| TV/DTV | - | Television/ Digital television |
| V | - | Voltage |
| VNA | - | Vector Network Analyser |
| WPT | - | Wireless Power Transfer |
| WSN | - | Wireless Sensors Network |
| $Z(\omega)$ | - | Free Space Impedance |
| Z_o | - | Output Impedance |

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CHAPTER 1

INTRODUCTION

This chapter describes in detail the research background, focus, problem statement, research objectives, research scopes, and the contribution of this study.

1.1 Research background

Up now, batteries have been utilized as a significant energy source for portable or wearable devices. In contrast, this way has many intrinsic drawbacks, such as batteries' total weight and size that occupy a significant fraction of an electronic system. The advantage of modern electronics brought about an interest in energy harvesting. As technology progressed, smaller electronic devices with lower power demands became available. It became possible to harvest energy from the environment to power these electronic devices or recharge a secondary battery. This technique is called Energy Harvesting (EH), which means powering wireless electronic devices by scavenging low-grade ambient energy sources such as environmental vibrations, human power, thermal, solar and their conversion into useable electrical energy [1]. There are many ambient sources for EH, such as light, thermal gradients, sound energy, wind energy, and radio frequency (RF) energy. Among several ambient energy sources, RF energy is available continuously for both indoor and outdoor environments throughout the day/night due to cell phone towers, satellites, radar stations, Wi-Fi routers, and other wireless devices/communication networks. Furthermore, an RF energy harvesting system is inexpensive and requires less infrastructure compared to different types of ambient energy sources [2]. Rectifying antennas (rectennas) consist of an antenna, matching circuit and rectifier, which is the current solution for capturing RF energy via antenna and converting it to DC power by rectifier circuit. However, the large size

and low efficiency of the antenna are critical challenges that need to be considered in dealing with low power ambient electromagnetic (EM) waves energy [3]. Several researchers have used conventional antennas such as microstrip antenna in an array form to achieve a long-distance wireless power transfer (WPT) and higher output DC power. However, there still are some conflicts, such as relatively higher loss of array feeding networks, difficulty in feeding network design, and antenna element coupling causing reduced rectenna array performance [4]–[7]. Nowadays, metamaterial-inspired rectenna design methods have been explored to overcome these challenges. Metamaterials are made of a three-dimensional ensemble of electrically-small resonators [8]. Unlike the absorbers, metamaterial-harvesters can absorb the incident EM energy and conduct the induced current to the load. The split-ring resonators (SRR) [9] and complementary split-ring resonators (CSRR) [10] are applied as energy collectors for energy harvesting applications [11].

Metasurfaces are considered as two-dimensional (2-D) version of 3-D metamaterial originally called metafilm, in which the surface is a distribution of electrically small scatters [12]. This advantage makes metasurface much simpler to fabricate than bulk metamaterials [13],[14]. Owing to their small losses, low profile, and rich electromagnetic field manipulation, metasurfaces are excellent spatial processors capable to manipulating electromagnetic waves with ever more complex possible applications such as polarization transformation, generalized refraction and non-reciprocal field control. To produce a desired scattered field, metasurfaces are usually made of uniform or non-uniform arrangements of specifically engineered sub-wavelength scattering particles [14]. The most critical feature of metasurfaces is giving a new degree of freedom to control the amplitude, phase, polarization response with sub-wavelength resolution and realize wavefront shaping within a distance much less than the wavelength [15].

1.2 Problem statement

Wireless devices need energy as their primary source of power to keep running. However, batteries, which are often used to power wireless devices, have a limited capacity and a finite lifespan. As a result, wireless devices and networks will not be achieved a sustainable operation. Energy harvesting from current energy sources in the ambient has emerged as a promising technology to overcome this challenge. RF energy can obtain from EM waves over a large area. EM waves generated by RF energy sources in various frequency bands are ubiquitous and available even in inaccessible locations, extracting energy from a large area. Furthermore, the use of low-power wireless devices is on the growth. For applications such as wireless sensor networks (WSNs) and the internet of things (IoT), RF energy harvesters provide a viable energy source.

Currently, rectenna system harvests the EM energy via antenna and converts it to DC power within a rectifier. An antenna is the main part used in array form to increase the harnessed power in the energy harvesting applications where a large amount of power is required. However, the large size and low efficiency are two critical challenges that need to be considered dealing with low-power ambient EM waves energy [15], [16]. A relatively large dimension of conventional antennas comparable to a half free space wavelength imposes certain limitations on using traditional antennas in array form as energy collectors in the rectenna systems. Furthermore, by using conventional antennas array require a distance $\lambda/2$ between the antennas to avoid destructive mutual coupling between array elements [17]. In addition, the limited functionality of the receiver antenna to collect EM waves energy with different polarization and incident angles is another limitation in the current harvesting systems.

Nowadays, metasurface inspired rectenna design methods have been explored to overcome these challenges. It is shown that in contrast to conventional antennas, close placement of metasurface collectors in array form does not deteriorate the power harvesting efficiency of the array and provide wider frequency bandwidth in comparison to traditional antennas. Moreover, the metasurface collectors can capture EM wave energy from ambient with the different incident and polarization angles. In this work, a broadband, polarization-insensitive and wide-angle reception is designed

for energy harvesting applications. The proposed absorber achieved a higher absorptivity across a wider frequency range at different polarization and incident angles from 0° to 60° , where the most absorbed power can be converted into a usable power. Therefore, the research provided metasurface structures as RF energy collectors for Wi-Fi applications. The proposed metasurface structures are achieved a higher AC conversion efficiency at different polarization and an incident angles from up to 60° .

1.3 Objectives of the research

This project aims to design and develop a cost-effective and efficient EM based energy harvester that can operate in the microwave regime. The work is broken down into the following objectives:

- I. To design and analyse a broadband metasurface based energy absorber with lumped elements for RF energy harvesting applications.
- II. To design and analyse a wide-angle metasurface collector for RF energy harvester at 5 GHz band.
- III. To design and analyse the metasurface array collectors for RF energy harvester with one load using corporate feed network at 5 GHz band.

1.4 Scope of the research

The research focused on studying metasurface structures used as energy collectors instead of conventional antennas. The scopes of this work include:

- I. Analyse and study the ability of the metasurface structures for EM harvesting at the microwave regime.
- II. The metasurface based energy absorber is designed at a broadband frequency range from 1 GHz to 7 GHz for EMC applications, mobile (GSM bands), Wi-Fi, 5 G bands, etc. the FR4 material with a thickness of 1.6 mm and a dielectric constant of 4.3 is used as substrate material. An air gap with a thickness of 14 mm is placed between the substrate and ground to enhance bandwidth. The

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List of Publications

Journals

1. Amer, A. A. G., Sapuan, S. Z., Nasimuddin, N., Alphones, A., & Zinal, N. B. (2020). A comprehensive review of metasurface structures suitable for RF energy harvesting. *IEEE Access*, 8, 76433-76452. (**published, ISI, IF=3.367-Q1**).
2. Amer, A. A. G., Sapuan, S. Z., Abdullah Alzahrani, Nasimuddin, N. Ali A. Salem and Sherif S. M. Ghoneim. Design and Analysis of Polarization-Independent, Wide-Angle, Broadband Metasurface Absorber Using Resistor-Loaded Split-Ring Resonators. *Electronics* (**Published- ISI, IF=2.4, Q2**)
3. Amer, A. A. G., Sapuan, S. Z., Nasimuddin, N. Wide-Angle Polarization-Independent Metasurface for Electromagnetic Energy Harvesting. *Journal of Electromagnetic Waves and Applications Engineering* (**under review- ISI, IF=1.34, Q4**)

Proceeding

1. Amer, A. A. G., Sapuan, S. Z., & Nasimuddin, N. (2020, September). Efficient Metasurface Absorber for 2.4 GHz ISM-Band Applications. In *2020 IEEE Student Conference on Research and Development (SCOReD)* (pp. 471-474). IEEE (**Scopus**).
2. Amer, A. A., Sapuan, S. Z., & Zinal, N. B. (2021). Metasurface with Wide-Angle Reception for Electromagnetic Energy Harvesting. In *Proceedings of the 11th National Technical Seminar on Unmanned System Technology 2019* (pp. 693-700). Springer, Singapore (**Scopus**).

3. Amer, A. A. G., & Sapuan, S. Z. (2022). Multi-band Metasurface Microwave Absorber Based on Square Split-Ring Resonator Structure. In *Proceedings of the 12th National Technical Seminar on Unmanned System Technology 2020* (pp. 373-382). Springer, Singapore (**Scopus**).
4. Amer, A. A. G., Sapuan, S. Z., Nasimuddin, N., & Hassan, M. F. (2021, March). A Broadband Wide-Angle Metasurface Absorber for Energy Harvesting Applications. In *2021 International Conference of Technology, Science and Administration (ICTSA)* (pp. 1-4). IEEE (**Scopus**).
5. Amer, A. A. G., Sapuan, S. Z., Zulkefli, N. A., Nasimuddin, N., Zinal, N. B., & Hamzah, S. A. (2021). Antenna Calibration in EMC Semi-anechoic Chamber Using Standard Antenna Method (SAM) and Standard Site Method (SSM). In *Proceedings of the 11th National Technical Seminar on Unmanned System Technology 2019* (pp. 605-616). Springer, Singapore (**Scopus**).
6. Amer, A. A. G., Sapuan, S. Z., & Nasimuddin, N. (2021, November). Wide-Coverage Suspended Metasurface Energy Harvester for ISM Band Applications, *IEEE Student Conference on Research and Development (SCOReD)* (**Scopus**).

List of Awards

1. **IEEE AP/MTT/EMC MALAYSIA JOINT CHAPTER BEST PAPER AWARD 2020** for the paper entitled “A comprehensive review of metasurface structures suitable for RF energy harvesting” published in: IEEE Access 2020.

2. **SILVER MEDAL** for “Wide Incident Angle Metasurface for Ambient Electromagnetic Energy Harvesting” at International Research and Symposium and Exposition (RISE) 2021, Universiti Tun Hussein Onn Malaysia (UTHM).