Novel Metasurface based Microstrip Antenna Design for Gain Enhancement RF Harvesting

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Abstract—**This paper presents an enhancement in radio frequency (RF) harvesting for conventional patch antenna using a metasurface layer (MSL). The key point behind such enhancement is inspired by Friis' equation which states; increasing the antenna gain leads to an increase in the received power. To achieve this goal, a MSL consists of 5×5-unit cells of a modified Jerusalem cross are proposed. The proposed MSL provides gain enhancement of about 10 dBi while the gain of the patch antenna is about 1 dBi. The proposed MSL is fabricated, compacted to the antenna and experimentally characterized. The empirical results indict an excellent agreement with the numerical results in terms of |S11| and radiation patterns. In addition, a set of RF harvesting measurements are made for patch antenna with and without the MSL. The comparison between measurements shows a significant enhancement in the output voltage when the MSL is involved.**

Index Terms—**MTL, gain control, RF harvesting, Friis.**

I. Introduction

Radio frequency (RF) harvesting is conceptually an energy conversion method employed for converting energy from the electromagnetic field into the electrical domain (i.e., currents and voltages) [1]. Therefore, design of an RF harvesting system needs to interface between the electromagnetic fields and the electronics circuits.

RF energy harvesting was proposed to make use of the power from the ambient electromagnetic signals within the microwave range such as TV, GSM, and Wi-Fi signals [2].

Despite the fact the RF source has the lowest power density, the privilege of RF energy is the broadest availability compared with the solar radiation and infrared thermal energies in terms of weather, time, and location. This reason makes RF energy harvesting promises to produce energy meets the requirement of low-power budget sensors, devices, and systems [3].

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The history of RF energy harvesting back to 1905, when Nikola Tesla (1856-1943) proposed wireless power transfer as a means of electrical energy transfer [4]. Later in the 1950s, an RF energy harvesting system was used for space microwave power-beaming applications and powering autonomous drones [5].

However, growing in low-power electronics systems make RF energy harvesting system desirable sub-system in some applications. Therefore, many researches have been conducted to meet the new require. As can be referred [6], multiple antennas have been proposed to increase the amount of energy derived from a given space by an energy-harvesting device. [7] presented a battery-free programmable sensing and computational platform for radio frequency identification (RFID) applications. [8] Proposed a high-efficiency harvester that can harvest low input RF power effectively. The researchers in [9] presented a design of monopole antenna with circular polarization for RF harvesting for wireless sensor node. The author of [10] utilized shorted ring slot antenna for circular polarization in GSM 900 band. In [11], circular polarization is formed via differentially-fed while the omnidirectional antenna is realized by compacting back-to-back patch antenna. Researchers of [12], the circular polarization was made via slotted-two circular-patch radiator with an electromagnetic coupling feed. A dipole antenna array with sequential rotation feeding was introduced in [13]. Researchers of [14] discussed a design and analysis of RF harvesting system consists of a microstrip patch antenna and three-stage Cockcroft-Walton rectifier.

In work [15], the authors proposed an efficient and low-cost RF energy harvester operating at 2.4 GHz. The proposed system comprises of a microstrip patch antenna, a filter, rectifier as well as a matching circuit. In [16], the researchers proposed a novel compact dual-circinal antenna with an omnidirectional characteristic for RF power transmission. Besides, a new approach to decrease the antenna size, was discussed. A patch of tapered-slit octagonal-shaped was employed to achieve the circular polarization as well as wide-beam in [17]. Authors of [18] proposed a hexagonal-shaped microstrip patch antenna with an objective to achieve an antenna with good radiation performance and better impedance matching. In [19], the authors proposed a novel broadband, wide-angle and back-to-back microstrip antenna for RF harvesting.

On the other hand, MSL has been employed for RF harvesting by two paths of researches. The first path uses MSL to enhance the receiver antenna performance. As in [20], the authors presented this idea by design an electrically small rectenna at the global positioning system (GPS) L1 frequency (1.5754 GHz) with a metamaterial-inspired near-field resonant. The key point of [21] was to match the input impedance of the rectifying circuit. Researchers of [22] proposed a wireless power harvester based on a rectifier, and antenna added to hybrid frequency selective surface. The second path of researches applied MSL as a RF harvester directly instead of the receiver antenna. [23] Proposed a design of dual-polarization and multi-focus near-field focusing reflective MSL for wireless power transfer.

The second research path has been inspired by the idea of perfect electromagnetic absorber introduced in [24]. Authors of [25] present a design for absorbing metamaterial with near-unity absorbance where the proposed structure consists of two resonators of metamaterial that couple separately to electric and magnetic fields. In [26], a design of MSL with polarization-insensitive characteristics and wide-angle of the reception was proposed for electromagnetic energy harvesting. Authors of [27] proposed an electromagnetic energy harvester based MSL array of 9×9 pixelated unit cells with dual-band and polarization-independent. The fundamental parts as a block diagram of the RF harvesting system are shown in Figure 1.

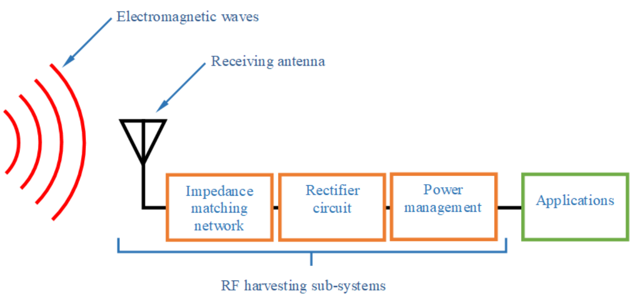

Figure 1; Fundamental parts of RF harvesting system.

The first part represents the receiving antenna (or the harvester antenna), where this part is responsible for converting the incident electromagnetic waves into an electrical signal. The second part is used to enhance harvesting via an impedance matching network. The third part is a rectifier circuit. Lastly, the produced power from the previous stage is managed by a power management sub-system.

This work is concerned with the first sub-system (receiving antenna) of the RF harvester and how to improve RF energy harvesting via improving the characteristics of this part. The second level of RF harvesting enhancement is based on the equation of Friis for the received power P_r [28]

$$P_r = P_t + G_t + G_r + 20\log\left(\frac{\lambda}{4\pi R}\right) \qquad (1)$$

where P_t is the transmitted power in (dB), G_t is the transmitter gain in (dBi), G_r is the receiver (or the harvesting antenna) gain in (dBi), λ is the wavelength and R is the distance between the proposed system and the transmitter in meters. Equation (1) clearly indicates that; increasing G_r leads to an increase the received power. In this work, a certain MSL will be employed to enhance the received antenna gain to enhance harvested power P_r.

II. ANTENNA DESIGN AND STRUCTURE

Figure 2 shows the design of the proposed microstrip antenna where the patch antenna is directly fed by a coaxial probe structure with a 50 Ω SMA port and located at $(x = 0, y = -4.5, z = 0)$ mm. The patch geometry is inspired from [29] based on truncated rectangular structure. As well as, the patch is etched to create four slots. The reason for using this technique is to enhance the antenna matching impedance below -10 dB, however, the radiation pattern symmetry could be ruined [30]. The antenna substrate is made of FR4 material with $\varepsilon_r = 4.3, \tan\delta = 0.0025$, and thickness of 2 mm. The substrate is designed to shape as a square of 280 mm side length. The details antenna dimensions are listed in Table 1.

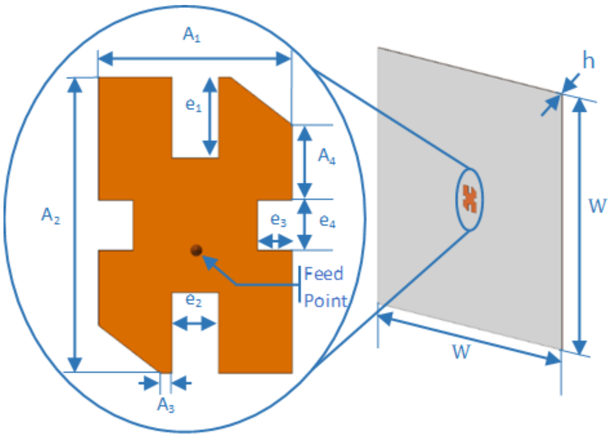

Figure 2; The proposed microstrip antenna structure.

TABLE I
THE PROPOSED MICROSTRIP ANTENNA DIMENSIONS.

Parameter	Dimension (mm)
W	280
h	2
A_1	19.31
A_2	27.43
A_3	1.17
A_4	6.98
e_1	7.51
e_2	4.66
e_3	3.44
e_4	4.65

The proposed antenna reflection coefficient and radiation pattern are clarified in Figure 3 for both simulated and measured results. The $|S_{11}|$ resonates at 2.47 GHz with about 1 dBi gain as seen in Figures 3(b)-(c). Besides, both simulated and measured results are splendid matched.

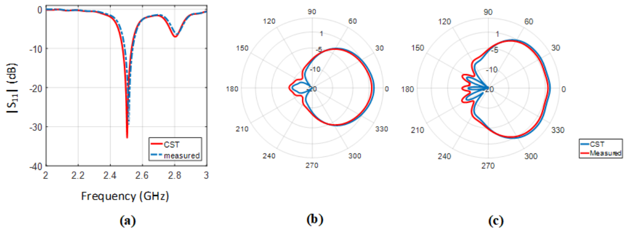

Figure 3; The $|S_{11}|$ spectra and the antenna radiation pattern based simulated and measured results for the proposed antenna: (a) the $|S_{11}|$ spectra, (b), and (c) the antenna radiation pattern at $\varphi = 0^{\circ}$ and $\varphi = 90^{\circ}$ respectively.

III. The Proposed MSL

The proposed MSL is an array of 5×5 unit cells. Each unit cell is constructed from Jerusalem cross-section plus four L-shape strips as seen in Figure 4. The unit cell dimensions are utilized to 60 mm, which is about λ/2. Choosing such dimensions is to avoid forming grating lobes [6]. The detailed dimensions of the proposed unit cell are clarified in Table 2.

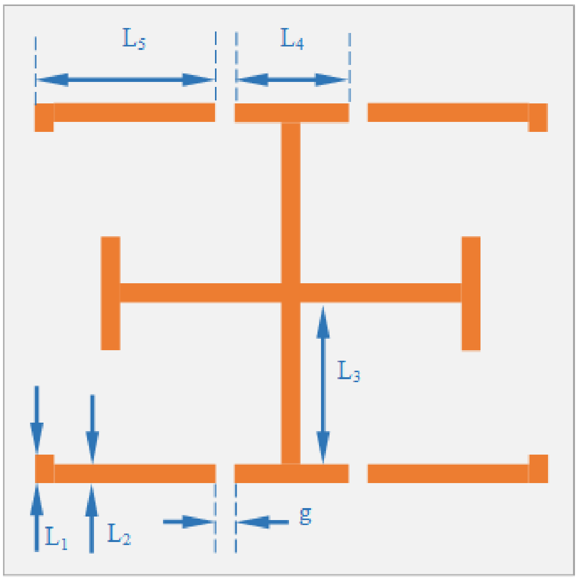

Figure 4; Unit cell structure.

TABLE II
UNIT CELL DIMENSIONS.

Parameter	Dimension (mm)
L_1	3
L_2	2
L_3	17
L_4	12
L_5	19
G	2

The proposed unit cell electromagnetic characterizations are tested numerically using CST MWS [31]. The proposed unit cell is positioned at the centre of a virtual waveguide as shown in Figure 5(a) to test the electromagnetic performance. The boundary conditions are selected as: the top and bottom sides (perpendicular on y-axis) are assigned as a Perfect Magnetic Conductors (PMC) while, the left and right sides (perpendicular on x-axis) are assigned as a Perfect Electric Conductors (PEC). TEM-modes are excited via two ports along z-axis as shown in Figure 5(a). For this, Figure 5(b) shows the magnitude of S_{12} for the two cases ON and OFF. It is important to mention that the authors decided to realize a resonant frequency for the unit cell at Logic-1 to 2.67 GHz for the design specifications [15], while, in case of Logic-0, the frequency resonance is completely disappeared from the frequency band of interest. Consequently, the maximum power transfer can be obtained at logic-1 only, while, the power transfer would be shut off at logic-0. The corresponding phase of the forward transmission coefficient S_{21} is plotted in Figure 5(c) for both statues ON and OFF. For statue-ON, the matching impedance occurs at the resonant frequency 2.67 GHz where the phase is zero degree. This phenomenon declares that the impedance's imaginary part is vanished and it confirms that the result of maximum power transfer can be obtained at logic-1.

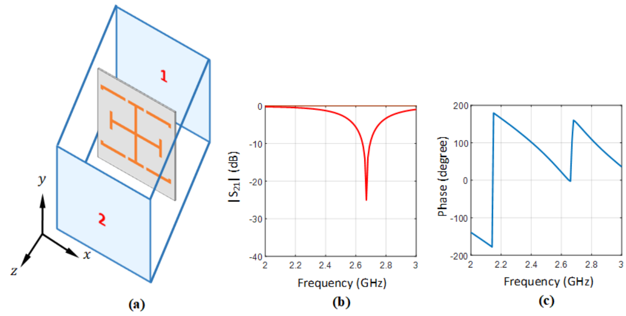

Figure 5; Unit cell performance characterizations: (a) Numerical setup, (b) the magnitude of S_{21}, and (c) phase performance.

In another aspect, Figure 6 shows the surface current distributions of the proposed MSL unit cell at phase $= 90^{\circ}$ of the incident wave. In general, it is found that the proposed MSL unit cell shows asymmetrical surface current distribution along the x- and y-planes due to the asymmetrical unit cell geometry along x- and y-planes. This realizes the phenomena of astigmatism affects, which effects on the radiation patterns, as will be seen later. Nevertheless, the surface current distribution is reached around 29 dBA/m at 2.65 GHz. This enhancement in the surface current distribution is achieved by the resonance at 2.45 GHz; which removes the reactive impedance parts to realize the maximum power transfer radiation [31].

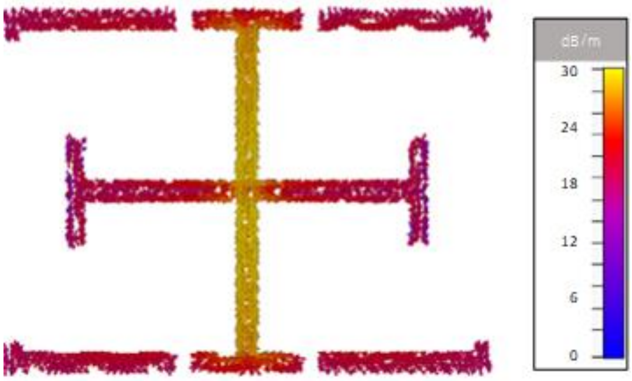

Figure 6; Surface current distributions of the proposed unit cell at 2.65 GHz.

IV. MSL LAYER DESIGN AND STRUCTURE

The proposed MSL layer is based on an array of 5×5-unit cells. To realize the configuration purpose, the MSL layer constructed from the proposed unit cell is mounted on a flexible thin layer of $0.1\ mm$ thickness, FR4 substrate. The overall individual unit cell dimensions are $60\ mm \times 60\ mm$, where the physical dimensions of the unit cell are $54\ mm \times 40\ mm$ as well as spaces between neighbored unit cells are $3\ mm$ on the x-axis and $10\ mm$ on y-axis. To ensure minimum coupling between unit cells, the periodicity of the unit cell is adjusted to be $60\ mm$ (~λ/2) [32]. Figure 7 shows the proposed MSL layer compacted to the microstrip antenna.

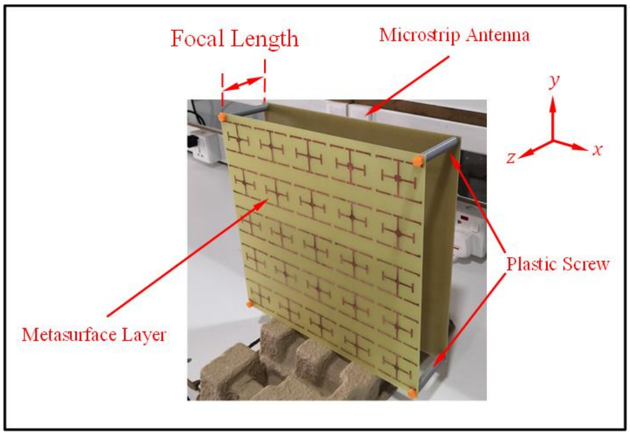

Figure 7; The proposed MSL layer with the antenna structure.

CST MWS is employed to study the best MSL location and array size with respect to the patch antenna. By changing the MSL array configuration size from 1×1, 3×3, and 5×5 and the patch antenna-MSL distance, the antenna gain is found to be significantly changing, as seen in Figure 8. To achieve 10 dBi gain enhancement, the MSL must consist of 5×5 unit cells and located at 70 mm in front of the patch antenna.

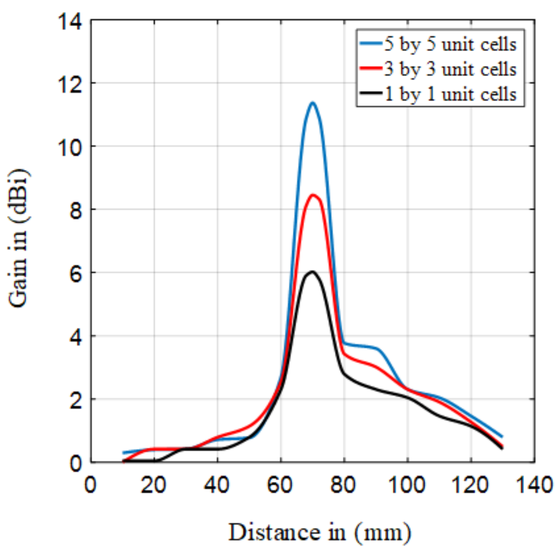

Figure 8; A parametric study for the proposed MSL array size performance.

In another aspect, Figure 9 shows S_{11} measurements of the proposed MSL systems with 2D radiation patterns at both E- and H-planes. In general, it is found that the proposed MSL layer shows symmetrical radiation patterns at both E- and H-planes in the boresight. This realizes the phenomena of the astigmatism solving by conducting the use of the proposed MSL array.

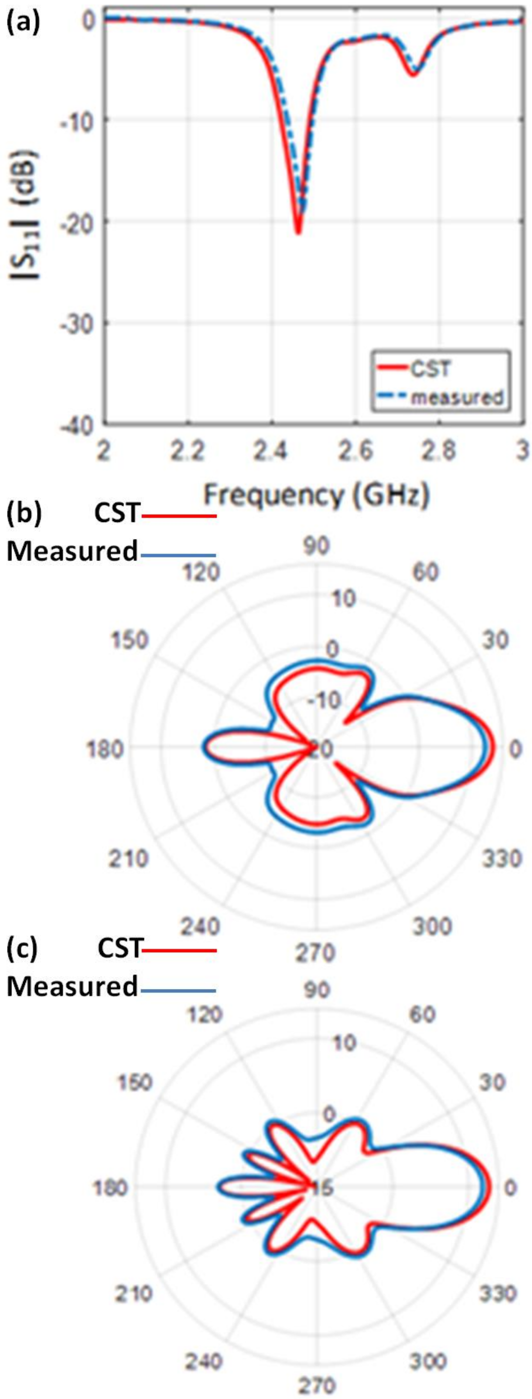

Figure 9; The proposed antenna systems measurements: (a) S11, (b) E-plane, and (c) H-plane.

V. Harvesting Measurements

RF harvesting measurements are conducted for the patch antenna and repeated for the patch antenna loaded MSL. Both measurements cases are submitted to the similar scenario where a transmitter fed by a voltage control oscillator (VCO) is placed at 0.5m, 1.0m, 1.5m, and 2.0m away from the proposed antenna based RF harvesting process is shown in Figure 10. The same transmitter is involved for all measurements. Hence, the transmitter gain does not affect the measurements.

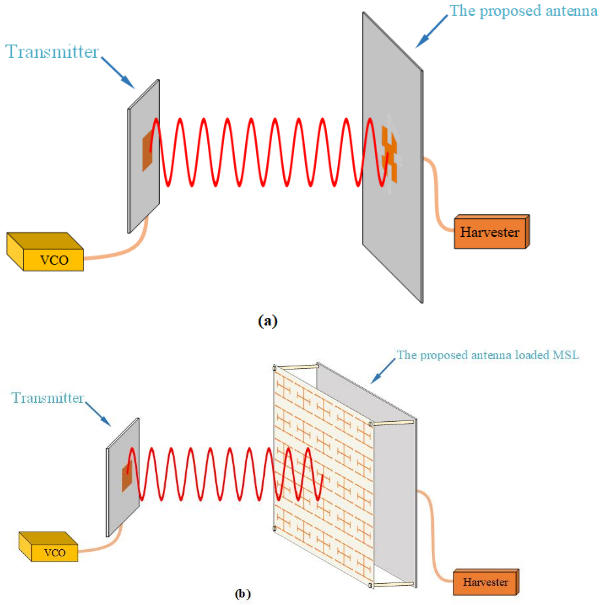

Figure 10; RF harvesting measurements: (a) The proposed antenna and (b) The proposed antenna loaded MSL.

The output DC voltage values from the RF harvester are described in Figure 11 when the load is 1 kΩ at 2.4, 2.45, and 2.5 GHz. The recorded measurements indicate two distinguished points. First, the output DC voltage levels decay generally when the separation distance between the transmitter and the proposed antenna increase. This behavior confirms the harmonic between measurements and the power inverse-square law. Second, the output DC voltages at 2.45 GHz when the patch antenna with MSL is found to be higher than other recorded results. This is due to the fact of MSL characterizes as a narrow bandwidth material.

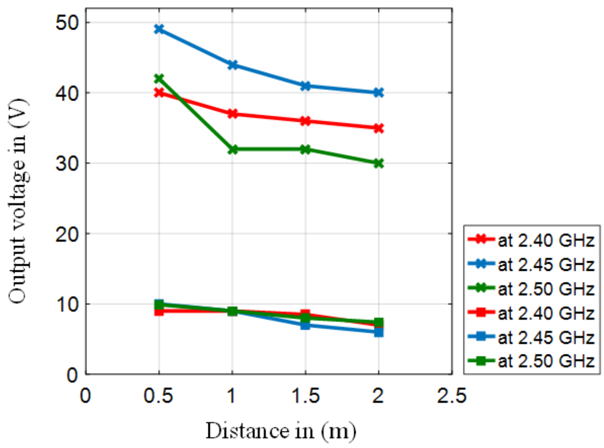

Figure 11; The output DC voltage from the RF harvester at 1 KΩ.

VI. Conclusions

RF harvesting measurements show distinguished improvement in the received power when the proposed patch antenna is loaded by MSL. The proposed MSL is designed as array of 5×5-unit cells of a modified Jerusalem cross. The MSL provides gain enhancement of 10 dBi. The empirical results of the proposed antenna-MSL indicate excellent agreement respecting RF harvesting. It is found that the proposed antenna realizes an excellent symmetry in the radiation pattern after the proposed MSL introduction. The proposed provides an excellent enhancement in the harvested output DC voltage due to the introduction of the proposed MSL structure.

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