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Numerical Investigation of a Polarization-insensitive Energy Harvesting Metasurface

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Abstract: This paper presents the numerical study of a polarization-insensitive energy harvesting metasurface. The proposed metasurface is designed to harvest ambient electromagnetic (EM) energy at 2.45 GHz. The basic constituent element of the metasurface is an electric-field-coupled (ELC) resonator, which is used to synthesize a 2 x 2 super-cell with polarization-insensitive features. Finally, the metasurface is realized as a 3 x 3 array of ELC super-cells, and presents an energy harvesting efficiency of 95.4% at 2.45 GHz. The achieved energy harvesting efficiency is maintained irrespective of the polarization of the incident excitation. The proposed metasurface configuration holds promise for the implementation of ambient EM harvesters, able to scavenge energy from wireless technologies operating in the 2.45 GHz band.

Index Terms: Electric-field-coupled resonator, energy harvesting, metasurface, polarization-insensitive.

1. Introduction

Future wireless communication networks are envisioned to provide seamless support for pervasive Internet-of-Things (IoT) deployments, and massive machine-type communications [1]. Furthermore, wireless sensor networks (WSNs) are gradually becoming ubiquitous, finding utility in environmental applications [2], e-health [3], industrial automation [4], precision agriculture [5], and various consumer applications, among others. For quite a number of these applications, traditional battery-powered implementations are not feasible, especially where the batteries themselves constitute an unwanted extra payload. It is therefore necessary to explore other ways to enable self-sustaining sensor nodes. The widespread availability of wireless communication technologies introduces a largely unused source into the energy space, namely ambient electromagnetic (EM) waves. Recent research has begun to explore various means of harnessing ambient EM energy to provide energy for low-power network devices.

As a consequence of their unique abilities to shape wave responses, metamaterials are attractive candidates for the implementation of EM energy harvesters. Metamaterial EM energy harvesters are generally based on the fundamental principles of metamaterial EM absorbers, which neither reflect nor transmit incident EM radiation. Metamaterial EM absorbers find ready application in the reduction of radio cross-sections, and the regulation of electromagnetic interference (EMI) [6]. Metasurfaces are the 2D equivalents of metamaterials, and are increasingly being harnessed to develop compact EM absorber structures, with very high absorption features [7–9]. As noted in [10], a single cell metasurface absorber typically consists of a dielectric substrate sandwiched between a top-layer conductive pattern and a bottom layer ground plane. The structure is tuned such that its impedance matches the free space impedance, while the presence of a ground plane ensures that the incident energy is dissipated in the dielectric material. If, however, the absorbed power is channelled to a load, the structure now becomes an EM energy harvester [11].

There have been several recent implementations of EM energy harvesters, based on the metasurface absorber principle. Popular unit cell configurations used in antenna designs, such as split-ring resonators (SRRs) and complementary SRRs [12,13], have found application in EM energy harvesters [14,15]. Recent studies have seen the implementation of fractal geometries also [16,17]. The electric field-coupled (ELC) resonator [18] has likewise been an attractive configuration, due to its simple design and strong broadside coupling to incident electric fields, which enable high energy harvesting efficiencies [10,19].

Typically, high energy harvesting efficiency is achieved when the harvester is optimized to interact with specific polarizations of the incident wave. In practical scenarios, however, EM energy must be harvested from incident waves whose polarizations are unknown beforehand. Although fractals [16,17] and other modified configurations [20] have been applied to implement harvesters able to respond to multiple polarizations, the realized geometric designs exhibit an appreciable level of complexity.

In a bid to employ simple geometric configurations, this paper, investigates the application of the simple ELC resonator structure to realize a metasurface with polarization-insensitive energy harvesting performance. To this end, the rest of the paper is organized as follows. Section 2 describes the geometry of the ELC unit cell, while Section 3 presents details of the parametric analysis and results. The paper is concluded in Section 4.

2. Geometrical Configuration of the Unit Cell

The unit cell configuration is based on a slightly modified ELC structure [10], which enables resonance with a compact configuration. The structure is modelled as a 2.56 mm thick Rogers TMM10i dielectric substrate (loss tangent, $\tan\delta =$ 0.002; dielectric constant, $\varepsilon_r =$ 9.8), sandwiched between a conducting top-layer ELC pattern, and a conducting ground plane. These two conducting layers are implemented using copper of thickness t = 35 µm. However, in contrast with the design in [10], the central gap on the ELC pattern is here employed as the port from which harvested energy is extracted. To this end, a resistor is placed within this gap, as a load into which harvested power is dissipated.

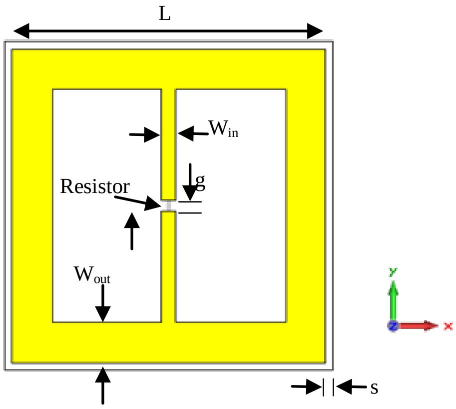


Fig.1. The modified ELC unit cell structure

3. Parametric Analysis and Simulation Results

The structure is modelled using the electromagnetic full-wave simulator, CST Microwave Studio (2015). Unit-cell boundary conditions are invoked, and simulations are performed using a floquet port excitation. The unit cell is excited using a y-polarized incident wave ($\phi = 0^0$) with a stimulated excitation port power $P_i =$ 0.5 W. The absorptivity of the structure, which indicates the level to which the unit cell absorbs incident energy, is given by the relation

$$A(\omega) = 1 - |S_{11}|^2 \tag{1}$$

where, s_{11} is the reflection coefficient arising from the reflection of incident wave energy by the structure.

3.1. Unit Cell Analysis

First, using an assumed resistance R = 50 Ω, the dimensions of the unit cell structure shown in Figure 1 are optimized for resonance at 2.45 GHz, as listed in Table 1. Results of a simulation of this structure are shown in Figure 2.

Table 1

Parameter	L	W_{in}	W_{out}	g	S
Value (mm)	10.9	0.5	1.4	0.4	0.5

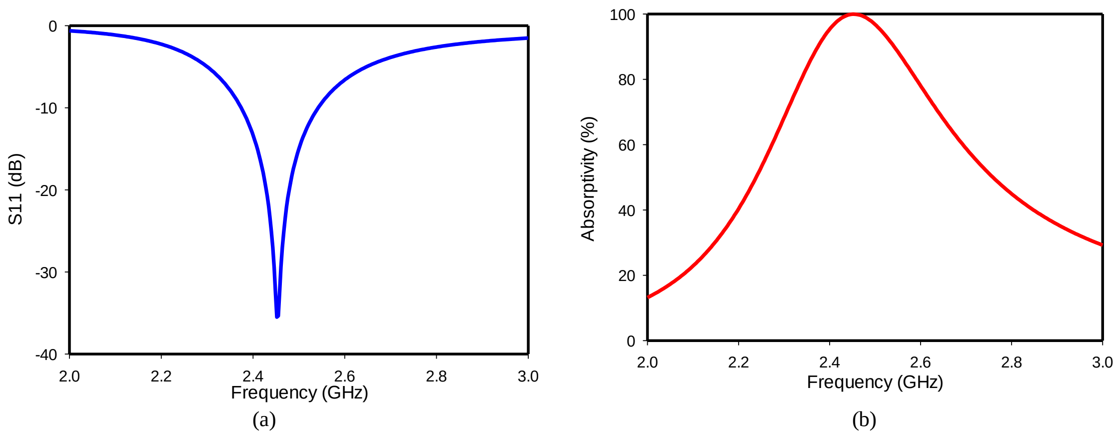


Fig. 2. Simulated performance of unit cell: (a) Reflection Coefficient, (b) Absorptivity

A reflection coefficient value of -32dB is obtained at 2.45 GHz. This suggests that the unit cell structure does not reflect energy at this frequency. This view is bolstered by the plot of the absorptivity of the structure as function of frequency. An almost perfect absorptivity of 99.9% can be observed at 2.45 GHz.

In order to track where the absorbed energy is dissipated as power in the structure, the power dissipation in each material constituting the unit cell under study is extracted as a percentage of the total dissipated power. To this end, the percentage dissipated power in each material is defined as

$$P_d = \frac{P_l}{P_i} \times 100\% \ . \tag{2}$$

where, P_l is the power loss in the material under investigation. In this study, the materials under scrutiny are the unit cell conductor layers, the dielectric substrate, and the resistor load. The percentage dissipated power in each of these materials is shown in Figure 3, as a function of frequency.

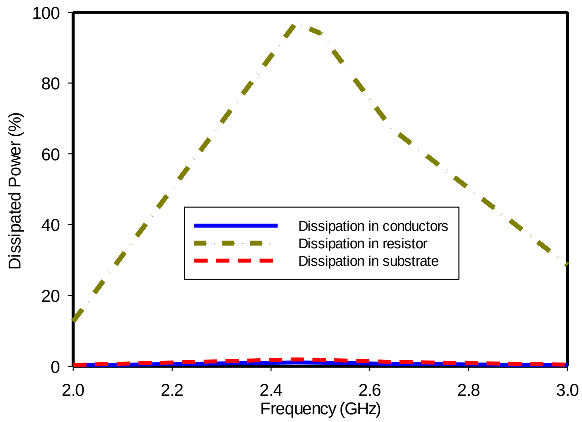


Fig. 3. Percentage dissipated power in materials comprising the unit cell

At 2.45 GHz, Figure 3 reveals that about 97.02% of the absorbed power is dissipated in the load resistor, with about 1.03% and 1.90%, dissipated in the conductor layers and dielectric substrate, respectively. This suggests that the bulk of energy absorbed by the unit cell structure can be harvested as an AC voltage across the resistive load. Consequently, the percentage dissipated power P_d in the load resistor defines the RF-to-AC conversion efficiency, otherwise known as the energy harvesting efficiency of the unit cell structure.

In order to examine the impact of the polarization of the incident excitation on the structure, the polarization of the incident excitation is swept in steps of 30^0 from $\phi = 0^0$ to $\phi = 90^0$, at which point the wave is now fully x-polarized. The simulation is repeated, and the reflection coefficients, absorptivities and RF-to-AC efficiencies are provided in Figure 4.

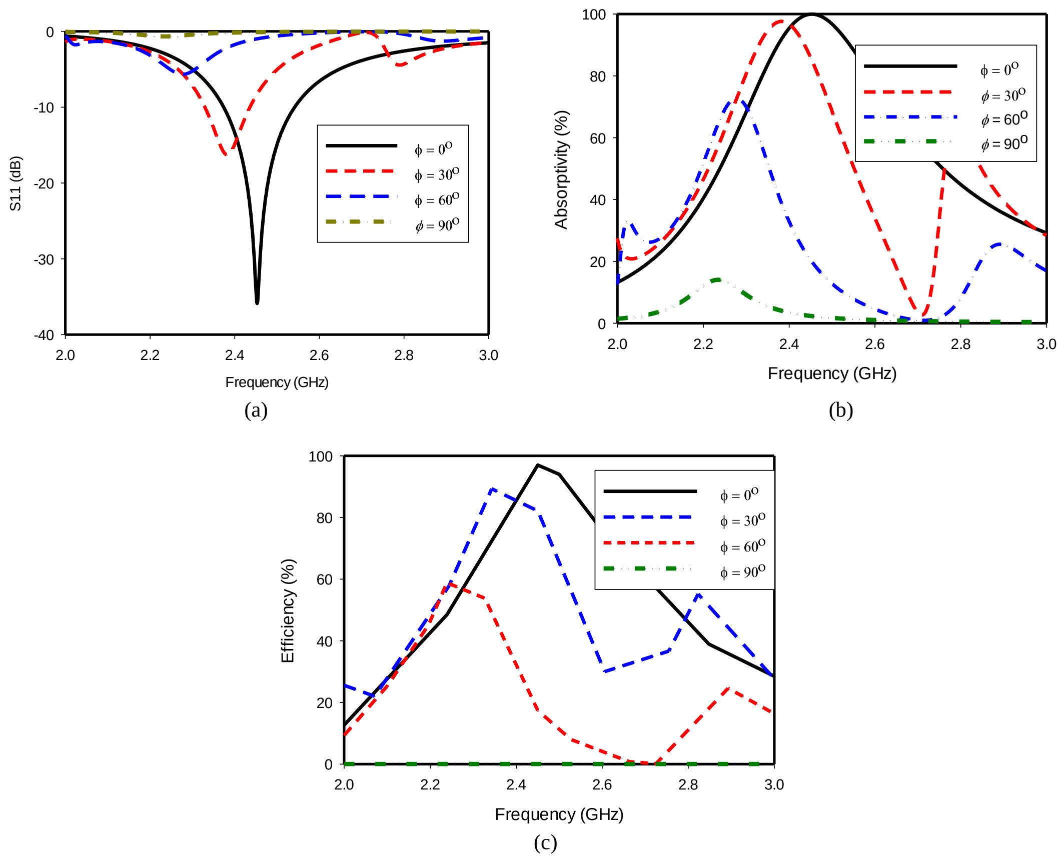


Fig.4. Impact of incident wave polarization on performance; (a) Reflection coefficient, (b) Absorptivity, (c) RF-to-AC efficiency

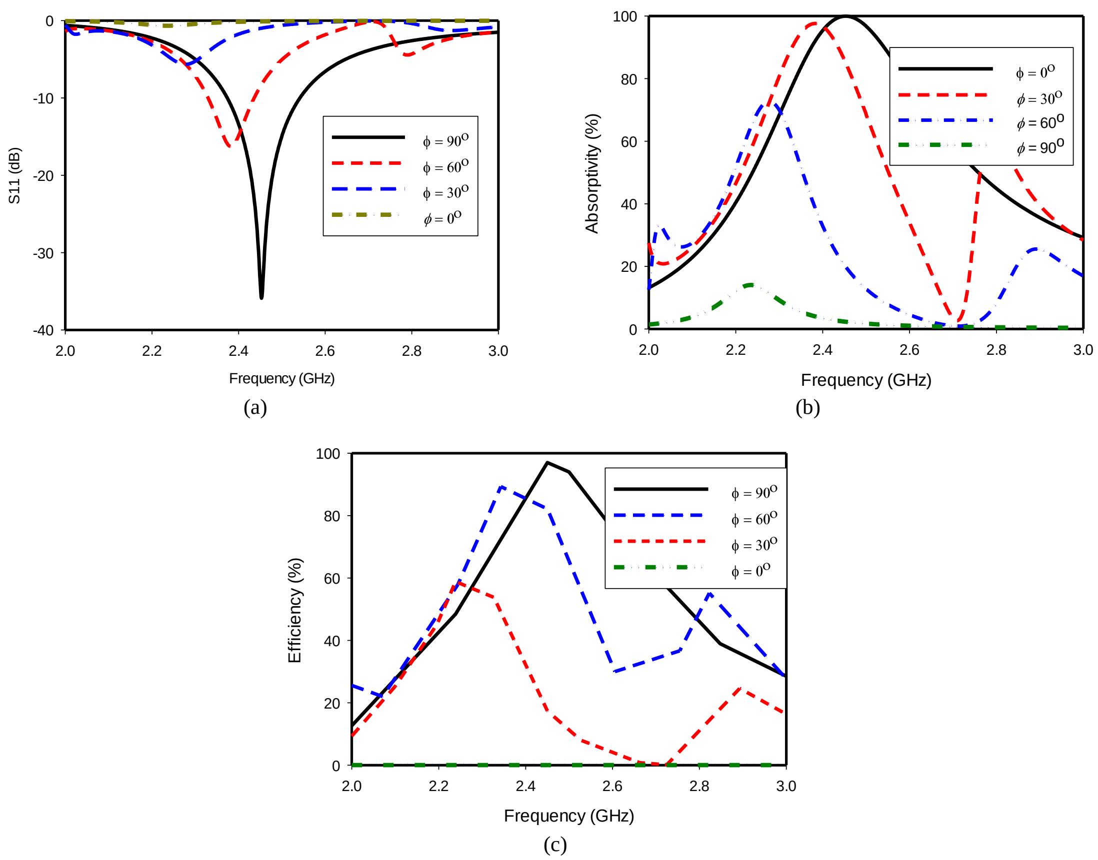


Fig.5. Impact of incident wave polarization on performance of rotated unit cell; (a) Reflection coefficient, (b) Absorptivity, (c) RF-to-AC efficiency

Figure 4(a) reveals an increase in the reflection of the incident wave as its polarization is changed from a y-orientation to an x-orientation. In the limit where the e-field component of the incident wave is parallel to the x-axis, it is completely orthogonal to the orientation of both the central arm of the ELC structure, and the embedded load resistor. The absorptivity exhibited by the structure at this orientation is then mainly due to energy absorption by the conductor layers and the dielectric substrate, which from earlier analysis, have been shown to be very low. This is the reason for the orthogonal polarization of the wave ($\phi = 90^0$) resulting in an absorptivity of just about 2.4%, as shown in Figure 4(b). At this point, Figure 4(c) shows that the RF-to-AC efficiency drops to zero, since practically no power is dissipated in the resistor by the orthogonally polarized incident wave.

Comparing Figures 2 and 4, it can be adduced that the absorptivity of the structure depends on the orientation of the central arm on the ELC pattern, relative to the polarization of the incident wave. Good absorption is achieved when the orientation of the central arm is parallel to the polarization of the incident wave. On the other hand, an orthogonally oriented central arm, relative to the wave polarization, results in negligible absorption. This is confirmed in Figure 5, which shows the performance of the unit cell structure after it has been rotated clockwise by 90^0 in the x-y plane, so that the orientation the central arm section lies along the x-axis, and parallel to the wave polarization. The results shown are largely a reversal of Figure 4. In this case, the reflection coefficient, absorptivity and RF-to-AC efficiency values improve as the orientation of the ELC central arm aligns with the x-polarized excitation.

3.2. Super-cell Analysis

The results presented thus far point to the potential for realizing a unit cell structure able to respond to orthogonal polarizations, by combining the normal ELC unit cell structure and its rotated variant in a super-cell arrangement. To this end, a 2 x 2 super-cell structure comprising of 2 normal and 2 rotated ELC patterns, is proposed. The configuration is chosen for symmetry, and is illustrated in Figure 6.

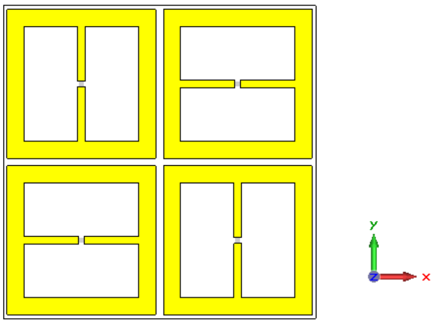


Fig. 6. 2 x 2 ELC super-cell

The cell dimensions are adjusted by optimization to offset the impact of mutual coupling between the constituent sub-cells, i.e. L = 9.7 mm, W_{out} = 1.12 mm. Furthermore, a parametric study of the impact of load resistance value on absorptivity and energy harvesting efficiency is carried out, as shown in Figure 7. To this end, the load resistance value is varied from 50 Ω to 200 Ω. Taking a cue from equation (2), the energy harvesting efficiency in this case is computed as the percentage ratio of total power dissipated in all 4 resistors to the incident power. In other words,

$$\eta = \frac{\sum P_l}{P_i} \times 100\% \quad (3)$$

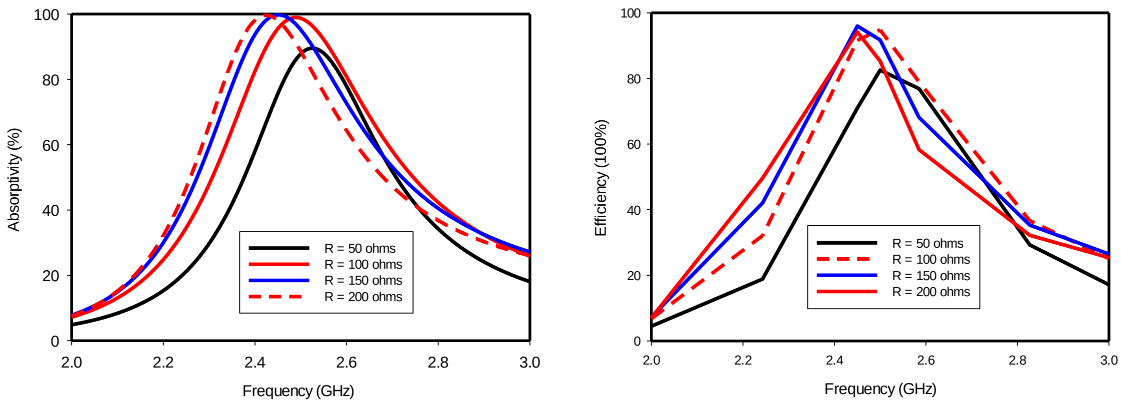
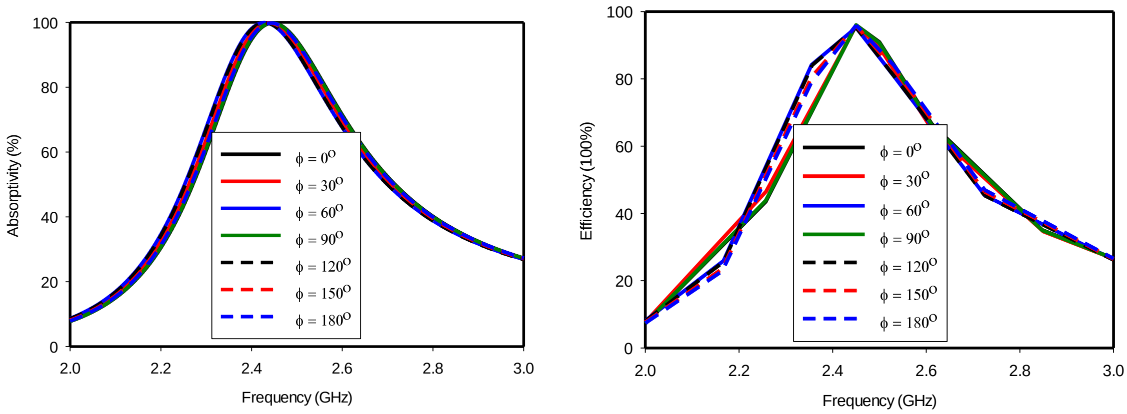


Fig. 7. Impact of load resistance value on super-cell: (a) reflection coefficient, (b) RF-to-AC efficiency

The results reveal that the initial 50 Ω resistance value is sub-optimal for the super-cell structure. Consequently, using the inbuilt optimizer of the full-wave simulator, an optimal value of 160 Ω is obtained for the load resistor. Using this value of load resistance, the optimized super-cell structure is excited with an incident wave whose polarization is swept from $\phi = 0^0$ to $\phi = 180^0$. The resulting absorptivities and RF-to-AC efficiencies are shown in Figure 8.



(a) (b)

Fig. 8. Performance of super-cell with optimal load resistance value: (a) absorptivity, (b) RF-to-AC efficiency

The results show that the structure achieves over 99% absorptivity and about 96% RF-to-AC efficiency values irrespective of the wave polarization. The can be explained by noting that for a y-polarized wave, the incident energy is dissipated in the sub-cells with vertical central arms, while for the energy in an x-polarized plane-wave is dissipated in the sub-cells with horizontal arms (Figure 6). For other intermediate angles ($\phi = 30^0, 60^0, 120^0, 150^0$), the dissipated energy is split between the resistors in the sub-cells in such a manner that their individual contributions sum up to the achieved level. This behaviour gives the super-cell configuration a polarization-insensitive energy harvesting characteristic.

3.3. Energy Harvesting Metasurface

Having established the polarization-insensitive energy harvesting potential of the proposed ELC super-cell, a 2D, 3 x 3 metasurface array, comprising of 9 super-cells, is modelled and simulated with the EM solver, and shown in Figure 9. The metasurface structure is excited using a plane-wave with normal incidence, and with an electric field strength of 1 V/m. Using the EM solver, the unit cell length dimensions and resistor values are optimized to L = 9.5 mm and R = 109 Ω, respectively, to compensate for the mutual coupling between cells of the finite 2D array. Furthermore, the polarization angle of the incident plane-wave is swept from $\phi = 0^0$ to $\phi = 180^0$, in order to study the impact of the polarization of the incident plane-wave on the energy harvesting efficiency, which is computed from equation (3) for 36 resistors. The results are presented in Figure 10.

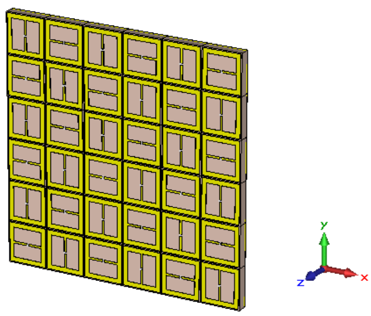


Fig.9. 3 x 3 energy harvesting metasurface comprising of 9 super-cells

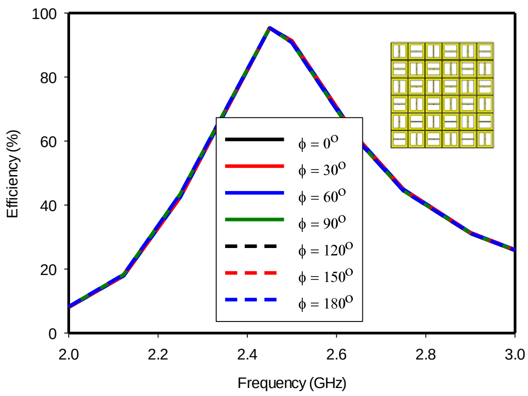


Fig.10. RF-to-AC efficiency of metasurface structure

The results reveal a high energy harvesting efficiency of 95.4% at 2.45 GHz, in addition to an insensitivity to the polarization of the incident plane-wave. This energy harvesting efficiency level compares favourably with similar recent metasurface configurations, with the added benefit of a compact size, as shown in Table 2.

Furthermore, the presented results show that the proposed metasurface structure holds promise for the harvesting of ambient EM energy arising from Wi-Fi usage in the 2.45 GHz band. For practical use, the load resistors can be replaced by rectification circuitry to enable the conversion of the harvested AC power into DC power, as may be required by various low-power electronic devices. The presented analyses show that the input impedances of such rectification circuits need to be optimized, along with the dimensions of the unit cell geometry, in order to maximally harvest electromagnetic energy.

Table 2. Comparison of proposed metasurface with related works

Reference	Simulated Efficiency	Unit cell size	Frequency
[21]	92%	0.147λ	3 GHz
[16]	96.5%	0.123λ	2.45 GHz
[22]	97%	0.27λ	2.4 GHz
[23]	88%	0.323λ	5.8 GHz
[24]	87.6%	0.193 λ	2.45 GHz
This work	95.4%	0.078 λ	2.45 GHz

4. Conclusion

This paper has presented the numerical analysis of a simple metasurface structure able to provide polarization-insensitive electromagnetic energy harvesting at 2.45 GHz. The investigation commenced by exploring the high absorption features of an ELC unit cell structure, showing that the bulk of absorbed energy can be harvested using an appropriately placed resistive load. Furthermore, the relationship between the orientation of the unit cell and the polarization of the incident wave was shown to have an impact on the absorption and harvesting performance of the unit cell. Insights gained from the analysis were applied to design a 2 x 2 ELC super-cell configuration, which exhibits polarization independence. Finally, a 3 x 3 metasurface, based on ELC super-cells, was shown to provide a high energy harvesting efficiency of 95.4%, irrespective of the polarization of the incident wave. This performance level shows that the proposed has a potential for efficient harvesting of ambient EM waves at 2.45 GHz.

In order to fully utilize the proposed design, there is a need for further investigations into replacing the load resistances with planar rectification circuitry, in order to realize the extraction of DC power. Also, the proposed configuration can be further studied to introduce wide-incidence angle features to the energy harvesting capability.

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