



Enhancement of Gain and Reduction of Backward Radiation Using Metasurface Antenna for Energy Harvesting Applications

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ABSTRACT

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A reflective metasurface technique is used to enhance the gain and reduction of backward radiation of an antenna. A normal metal slots is placed around the radiating patch to get the improved gain. Another metasurface antenna is placed with 10mm Gap from the radiating antenna to get the high radiation and enhanced directivity. A partial ground and line feeding with the conventional coplanar wave guide technique is used to improve the over all result. A rectifier circuit has been designed to harvest the electromagnetic energy to convert the DC output power. In the proposed model 8.1dB of Gain and -13.1dB of backward radiation with 2.82V of DC output power has been observed. The entire simulation and measurements has been done on HFSS and ADS software.

1. INTRODUCTION

Metasurface is one of the important techniques in the 5G technology to get the enhanced results with the miniaturized antenna [1]. By using the metasurface antennas a more RF energy can be harvested [2]. Generally metasurface antenna has a left handed properties which has both permittivity and permeability are negative with negative refractive index [3].

Rectenna (Rectifier + filter) is a significant technology for collecting electromagnetic energy from the receiving antenna [4]. The Impedance matching network, Rectifier circuit, and Voltage doubler circuit make up the Rectenna [5].

Over the past few years a lot of research has been going on in the field of wireless power transmission. Liu et al. designed a rectangular patch with the dual substrate and successfully achieved the 3.57 dBi of forward gain and 7.5 dBi of backward Gain [6]. Zhao et al. had designed the 4x4 complementary split ring resonator with the 74cmx74cmx1mm and achieved very low efficiency with the 35.1% of 10dbm of input power [7].

Behera et al. designed a partial ground metasurface aerial and obtained the 950MHz of the axial ratio Bandwidth with the 85% transmission efficiency [8]. El Badawe et al. have successfully achieved the 40% Ac to DC power conversion [9]. Aldhaeabi and Almoneef had proposed an antenna with the dual polarization with the 98% of AC to Dc power conversion efficiency [10].

Hu et al. has achieved the 25MHz of bandwidth at 2.45GHz of resonating frequency [11]. Zhang et al. had designed the stair case rectangular shape slots on the radiating patch and achieved the high of 4.5dBi of gain with the low bandwidth and low output power [12]. Ghaderi et al. simulated the rectangular slot with the 9x9 phased array and they found the very low bandwidth 100MHz at 2.4GHZ resonating frequency [13].

From the (Table 1) Literature review it was observed that the Most of the metasurface antenna with RF energy

harvesting applications has achieved low bandwidth and low Gain. This paper aims to design the metasurface antenna with the high Gain and high bandwidth to achieve the high output Voltage. Liu et al. 2019 [6] achieved the Gain of the designed antenna is 3.5dB and 12.8dB of the Backward Radiation. For the proposed antenna it was founded the Gain of the Antenna is 8.0 dBi and Backward Radiation is -13.1dB. In the proposed antenna the Receiving the antenna Efficiency is 93.5% with 113.5 of Front to back ratio.

Table 1. Literature review

Ref	Shape of the patch antenna	Bandwidth	Gain	Advantages
6	Rectangular patch with rectangular slots on the Ground plane	110MHz	3.57dBi	Achieved Low backward radiation
7	4x4 complementary split-ring resonator (CSRR) array	-	-	35.1% of efficiency had achieved at -10dB input power
8	Schematic diagram of proposed MTS with partialground antenna	5MHz	3.4dBi	Axial ratio bandwidth is 950MHZ
9	Plus shaped 8x8 array antenna with the dual substrate			Measured efficiency AC to DC conversion is 40%
10	Geometry of dual polarization of proposed MTS antenna	1.7GHz	-	Achieved the higher radiation efficiency 98%
11	MTS for unit cell with gap on Closed rectangular patch	25MHz	-	Efficiency was achieved for 2mm and 6mm air gap
12	Stair case spiral shape patch with CPW technique	25MHz	4.45dBi	Half power beam width =68.3°
13	Rectangular slot with plus shaped 9x9 array antenna	100MHz		Achieved 90% of efficiency higher for every polarization angle

In the section II antenna design is discussed with dimension and results has discussed in the section III whereas Rectifier circuit had discussed in the Section IV and the fabricated model presented in the Section V followed by the comparison table.

Table 1 shows the literature review of the metasurface antenna for RF energy harvesting applications. This paper focuses on design the metasurface antenna with High Gain and improve Bandwidth to achieve the high output Voltage.

In open literature, a good receiving antenna efficiency achieved by using reflector but not gain and bandwidth [7, 9-11, 13].

2. ANTENNA DESIGN

Metamaterial is the three dimensional in structure with the artificial medium, due to its negative permittivity and permittivity the Gain or radiation efficiency improved with the less dimensions of the antenna. The main drawback on metamaterial is manufacturing very difficult in the bulk quantity [14]. Metasurface is the two dimensional in the structure with the negative permittivity and permeability, due to its 2D structure it is very easy for manufacturing. So it is one of the booming technology in the present research [15].

As one of the most suitable antenna for the receiving the electromagnetic energy is the metasurface antenna. The proposed antenna has been designed with the dimensions 96mmx84mmx1mm of each substrate with the FR4 is the dielectric substrate.

A rectangular slot is present around the radiating patch antenna on the top substrate, and a 4x4 square form Defective ground shape is present on the reverse side. The FR4 substrate has a reflective metasurface with dimensions of 96mmx84mmx1mm, and the gap between the two substrates is 10mm. The backward radiation is eliminated by using a reflecting metasurface, which improves the antenna's gain and backward radiation.

Due to the Reflective metasurface the Backward radiation is reduced, so the receiving energy from the antenna is also improved. In this paper the Rectenna is designed with LC-impedance matching network with the Voltage Multiplier Circuit and achieved the 2.82V of DC voltage and 112μA of DC current.

The Figure 1 indicates the Geometrical view of the proposed antenna with the front view of the proposed aerial, Figure 2 shows the back view of the substrate 1. The Figure 3 shows the front view of the metasurface reflector. Figure 4 represents the back view of the metasurface reflector with the defective ground structure.

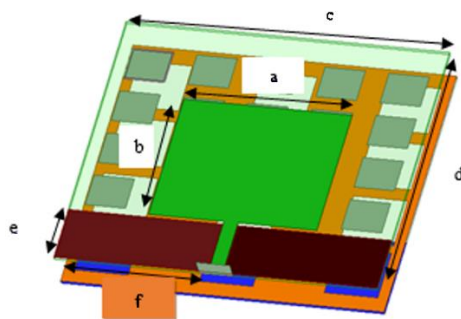


Figure 1. The characteristics of top view of proposed antenna

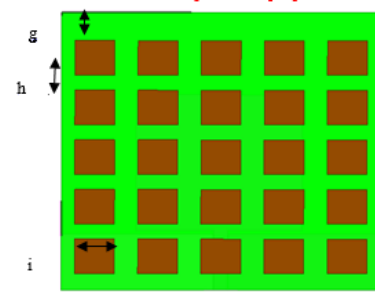


Figure 2. The characteristics of back view of the top substrate (back view)

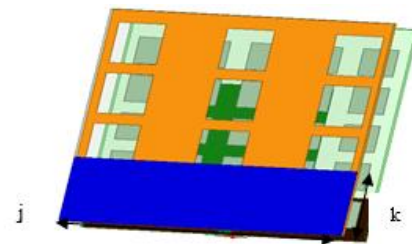


Figure 3. The characteristics of proposed aerial with the partial ground (back view)

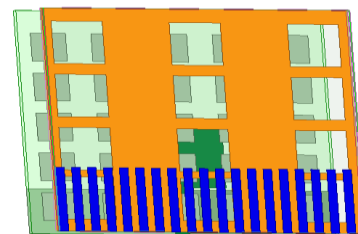


Figure 4. The characteristics of the proposed antenna with DGS (back view)

Table 2. Dimensions of the proposed aerial

Letter	Parameter	Dimension
a	Width of the Patch	$0.4\lambda_0$
b	Length of the Patch	$0.328\lambda_0$
C	Width of the Substrate	$0.768\lambda_0$
d	Length of the Substrate	$0.672\lambda_0$
e	Length of the Ground on the top substrate	$0.136\lambda_0$
f	Width of the Ground on the top substrate	$0.3656\lambda_0$
g	The Gap of the slot on the back side of the Top substrate	$0.065\lambda_0$
H	Length of the slot on back side of the Top substrate	$0.084\lambda_0$
i	Width of the slot on back side of the Top substrate	$0.096\lambda_0$
j	Width of the Partial Ground	$0.768\lambda_0$
K	Length of the Partial Ground	$0.201\lambda_0$

The Table 2 shows the dimensions of the suggested antenna and it is measured using the FR4 dielectric substrate. The size of suggested aerial is $0.768\lambda_0 \times 0.672\lambda_0 \times 0.008\lambda_0$ with the gap between two substrates are 10mm.

3. RESULTS AND DISCUSSIONS

In this section various aerial parameters can be discussed with the simulated and measured results.

A. Return loss

Return loss can be defined as the how much power is reflected back from the input terminal. Reflection coefficient is defined as [16].

$$\Gamma = \frac{v_{ref}}{v_{fwd}} \quad (1)$$

where, Γ is reflection coefficient.

For the designed antenna the reflected power is 52mW and the radiated power is 910.05mW. So the reflection coefficient is 58.31mW.

Return loss is calculated from

$$\begin{aligned} RL &= -20\log(\Gamma) \\ &= -24.68\text{dB} \end{aligned} \quad (2)$$

From the Eq. (2) the return loss is calculated as -24.68dB, whereas the by using the software it was founded for the designed aerial has been operated in dual band and the return loss is -24 dB at 2.4GHz frequency. It was observed that the 480MHz and 770MHz of bandwidths at 2.4GHz, 6GHz resonating frequency.

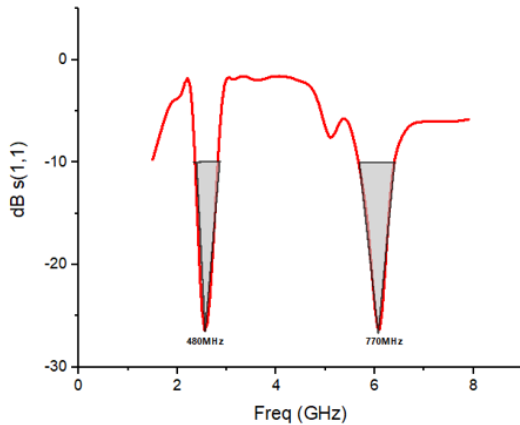


Figure 5. Return loss of the designed aerial

In the Figure 5 the shaded region shows the bandwidth of 480MHz for the designed aerial.

B. VSWR

VSWR is termed as voltage standing wave ratio. It is calculated by the Eq. (3)

$$vswr \approx \frac{1 - |\Gamma|}{1 + |\Gamma|} \quad (3)$$

where, Γ is reflection coefficient.

It was observed that the simulated VSWR for the designed aerial is 1.02. The Figure 6 shows the VSWR of the designed aerial.

C. Gain

In general gain is calculated by using the comparison method. Here the comparison can be done with the designed antenna with either dipole aerial or half dipole aerial or Isotropic antenna.

Directivity for the rectangular patch can be given by the Eq. (4) [16].

$$D = \frac{4(k_0 w)^2}{\Pi \eta G_{rad}} \quad (4)$$

where G_{rad} is radiation conduction of the patch, η is efficiency, k_0 planks constant.

In general gain cannot be less than directivity because the efficiency is in between 0 and 1.

$$G = \eta D \quad (5)$$

where, G is gain of antenna, η is efficiency, D is directivity of antenna.

It was founded that the gain for the designed aerial is 8.0dB and it is shown in the Figure 7.

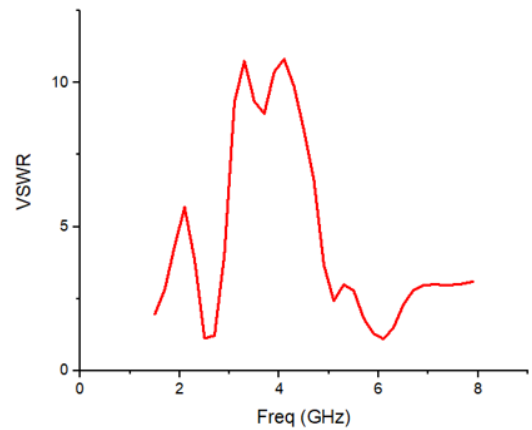


Figure 6. VSWR of the designed aerial

Gain Plot 1

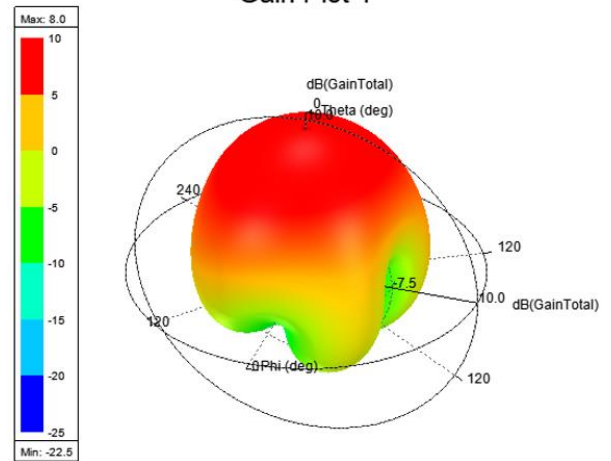


Figure 7. Gain plot of the designed aerial

D. Current distribution

The electric field of the radiating patch can be shown in the Figure 8 and the maximum electric field that can be represents in the red color. The Figure 8 shows the E-plane of the designed aerial and Figure 9 shows the H-plane of the designed aerial.

The magnetic field distribution on the radiating patch is given in the Figure 9 and the maximum magnetic field is 5.5A/m.

The maximum electric field for the designed antenna is 2019V/m and the maximum Magnetic field is 5.5A/m.

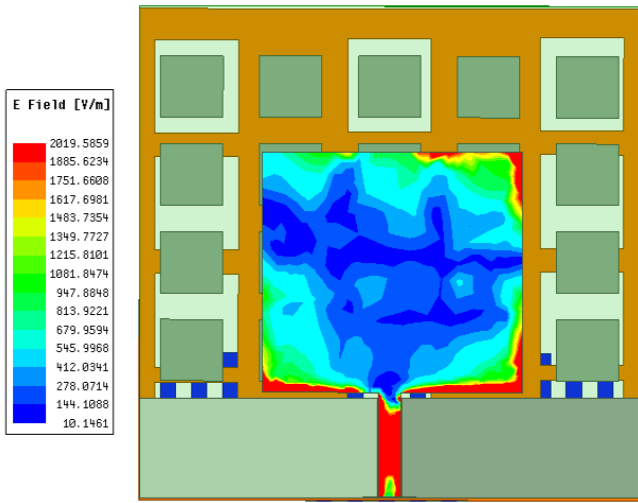


Figure 8. Electric field (E-plane) distribution of the designed aerial

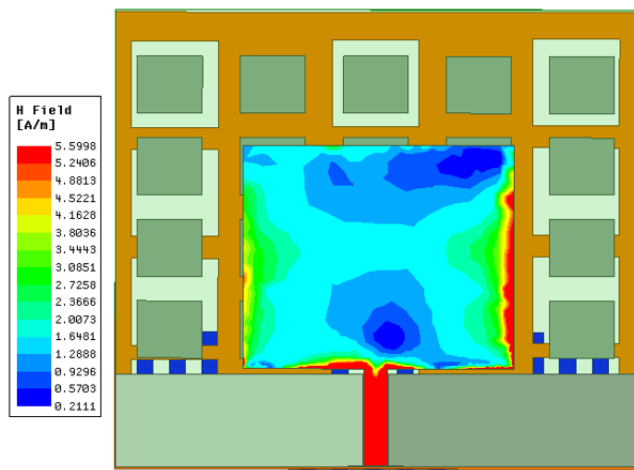


Figure 9. Magnetic field (H-plane) distribution of the designed aerial

E. Radiation pattern

Radiation pattern is defined as the “Mathematical representation of the radiation properties of an aerial” [16].

In general Radiation pattern is calculated by using the Eq. (6)

$$P_{rad} = \frac{1}{2} \operatorname{Re} \iint_S E_1 X H_2^* ds \quad (6)$$

$$= \frac{1}{2\eta} \iint \left(|E_\theta|^2 X |E_\phi|^2 \right) r^2 \sin \theta d\theta d\phi \quad (7)$$

The Eq. (7) shows the Radiation pattern of the Microstrip patch antenna. where electric field E within the patch is normal to the patch and the Ground and Magnetic field is parallel to the patch.

The Figure 10 and Figure 11 indicates E-plane and H-plane of the radiated metasurface antenna.

Backward radiation was -12dB with a gain of 3.5dB and a 10mm gap between the two substrates in the previous design [6]. However, with a 10mm of air gap between the two substrates, the suggested antenna's backward radiation is measured at -12.9dB.

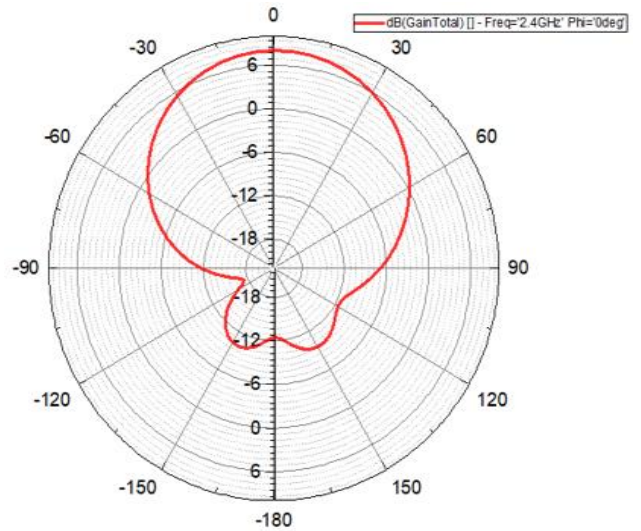


Figure 10. E-plane of the designed antenna at 2.4GHz

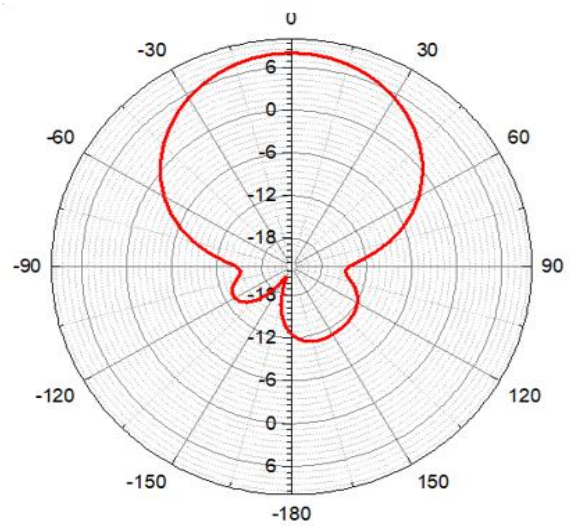


Figure 11. H-plane of the designed aerial at 2.4GHz

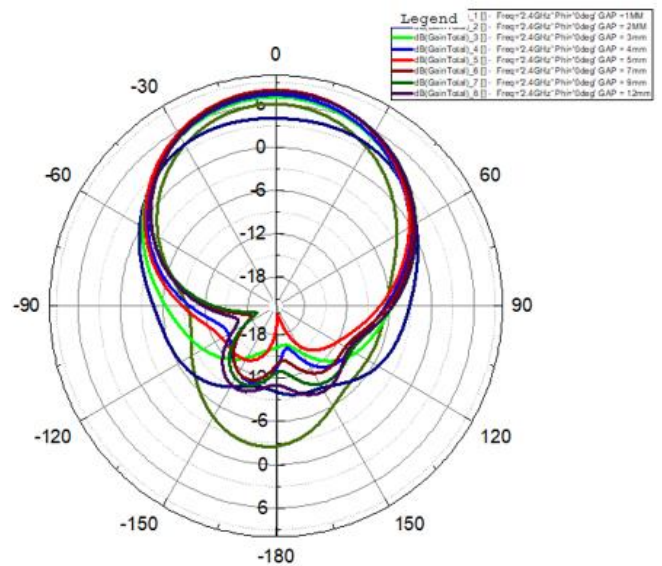


Figure 12. E-plane of the designed antenna by varying the Gap with the DGS at 2.4GHz

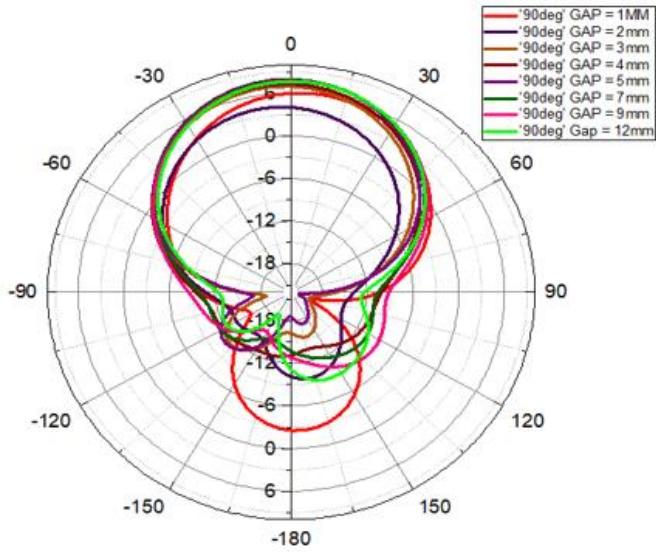


Figure 13. H-plane of the designed aerial by varying the gap with DGS at 2.4GHz

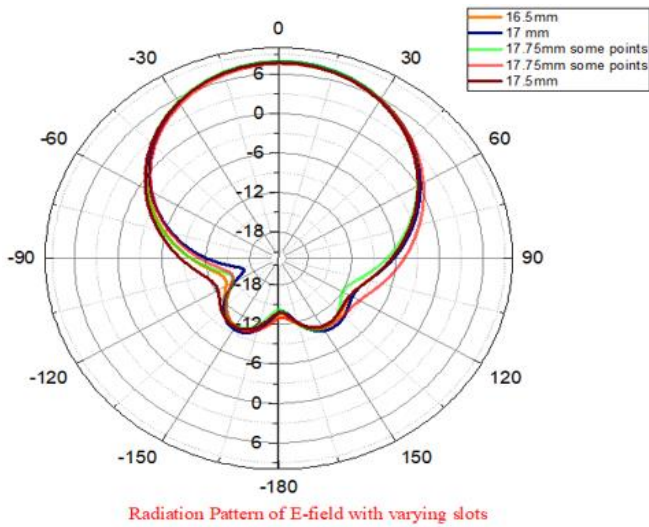


Figure 14. Radiation pattern of E-plane with varying the slots at 2.4GHz

F. Parametric analysis

The gap between the two substrates in the proposed aerial varied from 1mm to 12mm. The E-plane of the planned antenna is shown in Figure 12 and H-plane is shown in the Figure 13.

The backward radiation for the designed aerial is -12.9dB, although the Gain and radiation both modified by altering the distance. Figure 12 and 13 depict the aerial's radiation pattern as the gap for the E-plane and H-plane is varied. When the gap between the two substrates is small, the Backward radiation is large, and vice versa, implying that the gap is inversely proportional to the Backward radiation. As compared to previous designs, the backward radiation is very low after adjusting the gap at 10mm and 12mm.

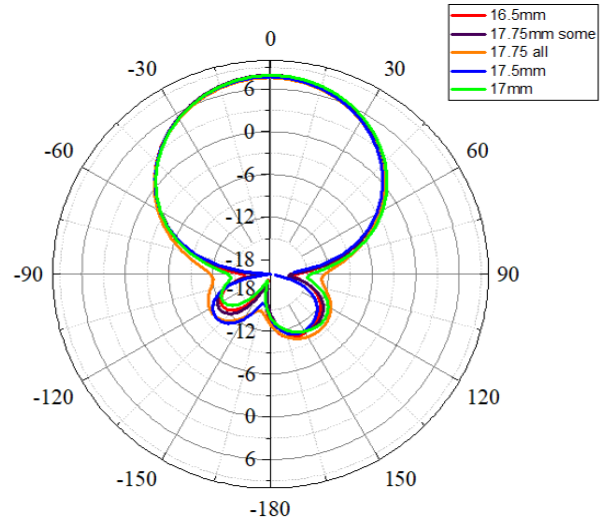
It was observed that by varying the slots width on the backside of the top substrate the radiation pattern can be vary which is shown in the Figure 14 and Figure 15.

G. Efficiency

In general efficiency is defined as the power radiated by the Microstrip patch antenna to the receive power [16].

$$\eta = \frac{\text{Radiated power}}{\text{Received power}}$$

For the designed antenna the efficiency is 93.35% with the front to back ration is 113.8.



Radiation Pattern of H-plane with varying slots

Figure 15. Radiation pattern of H-plane with varying the slots at 2.4GHz

4. RF ENERGY HARVESTING

Rectenna is one of the important techniques to harvest more electromagnetic energy from the receiving antenna. The Figure 16 shows the block diagram of the RF Energy harvesting.

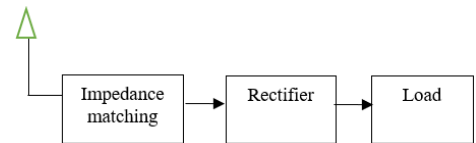


Figure 16. Block diagram of the RF energy harvesting system

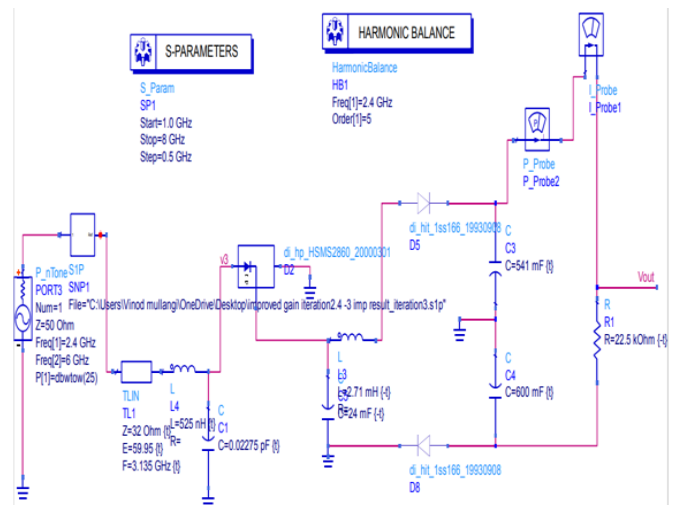


Figure 17. Rectifier circuit of the designed antenna

The block diagram of the RF energy collecting system is shown in Figure 16. The signal is received by the antenna once it has been transmitted and fed into the Impedance matching network. After matching the impedance, the signal is delivered into the Rectifier, which transforms the alternating current to direct current. It can then be transmitted into a Doubler circuit or a DC-DC Voltage Booster circuit to acquire the highest voltage, which can subsequently be supplied to the load.

For the designed aerial to receive signal from the receiving antenna, impedance matching network can be designed by using the TLIN (lambda/4 transmission line) with the LC matching network. The inductance and capacitance value is calculated by Eq. (8)

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (8)$$

From the Eq. (8), by taking the frequency as 2.4GHz then the inductance as 525nH and capacitance as 0.02275pf.

The Figure 17 shows the Rectenna designed using the HSMS2860 diodes. Two diodes are connected in forward and backward directions with two capacitors (c1= 541mf, c2 = 600mf) in the suggested circuit.

A. Return loss

From the reception of a signal from the receiving aerial. The signal is routed to the impedance matching network, which should match the desired frequency with the received signal. To determine whether the received signal is correctly aligned with the receiving aerial, the S11 parameter should be aligned with the receiving aerial which is shown in the Figure 18.

The Figure 18 shows the S11 parameter for the designed Rectenna. In the earlier harvesting circuit the maximum output voltage is 1.982V. In the designed circuit the output voltage is 2.82V which is shown in the Figure 19.

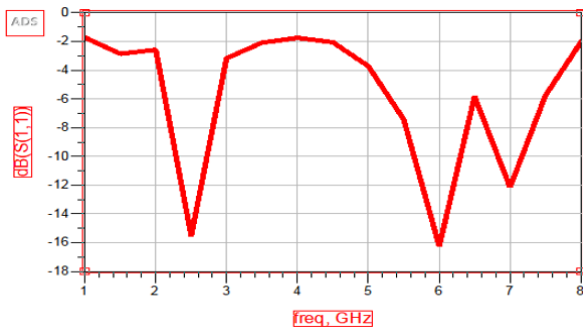


Figure 18. Return loss of the designed rectifier circuit output voltage

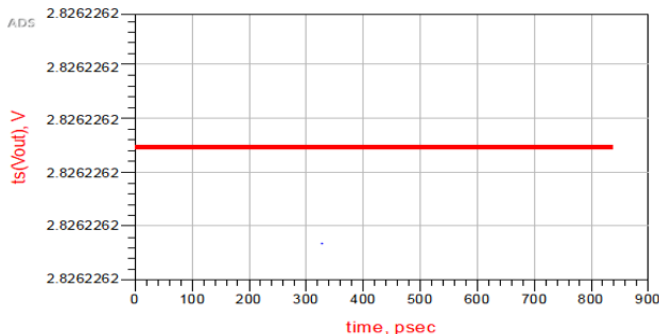


Figure 19. Output voltage for the designed circuit

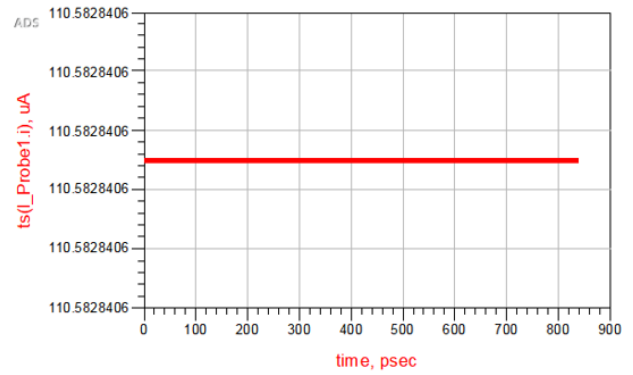


Figure 20. Output current of the designed circuit

The Figure 19 shows the output voltage of the Rectifier circuit is 2.82Volts and Figure 20 shows the output current of 110.58μf for the designed rectifier circuit.

5. FABRICATED ANTENNA

The Figure 21 shows the fabricated model of the proposed antenna. The designed antenna has fabricated on FR4 substrates.

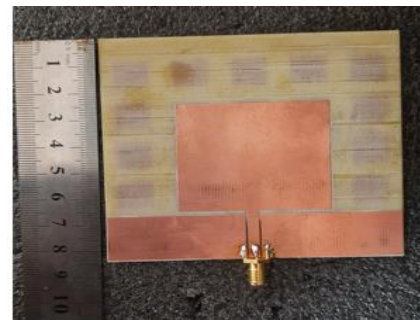


Figure 21. Fabricated antenna on top view

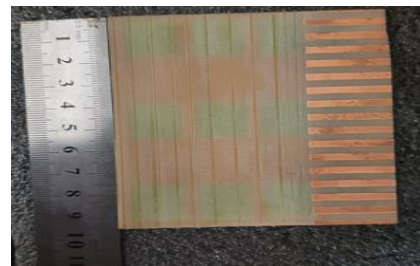


Figure 22. Fabricated antenna on back view

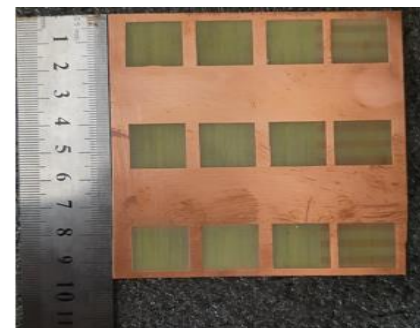


Figure 23. Fabricated antenna on front view of the bottom substrate

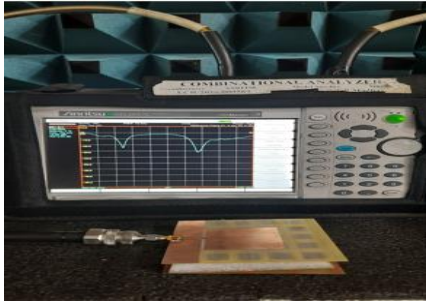


Figure 24. Measurement of the S11 parameter using network analyzer

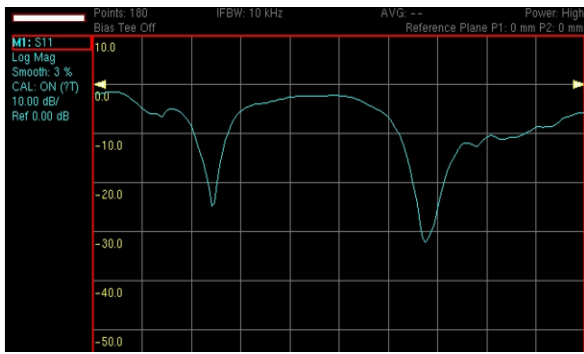


Figure 25. S11 parameter of the measured antenna

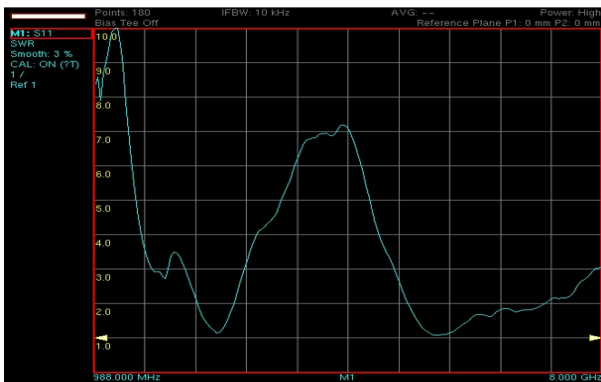


Figure 26. VSWR parameter of the measured antenna

Figure 22 and Figure 23 show the fabricated model of the back view & front view of the top substrate. Figure 24 and Figure 25 show the measuring of the S11 parameter using the

network analyzer. Figure 26 shows the VSWR measurement for the suggested aerial. It has been observed that the fabricated model exhibits the dual band frequency. Figure 27 and Figure 28 show the measured and simulated gain at 2.4GHz and 6GHz respectively.

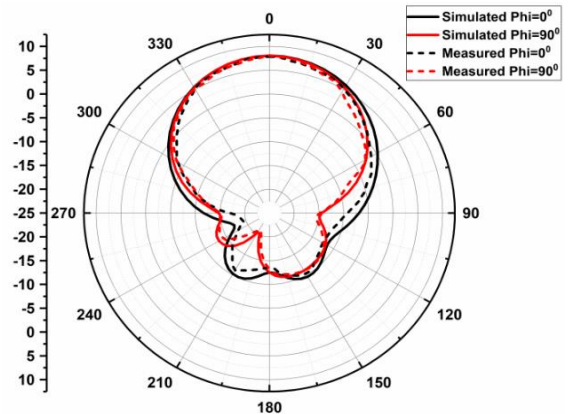


Figure 27. Radiation pattern of the designed antenna at 2.4GHz

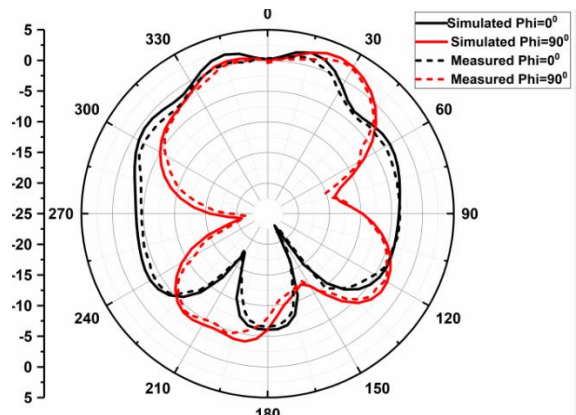


Figure 28. Radiation pattern of the designed antenna at 6GHz

6. COMPARISON

The Table 3 shows the comparisons of the proposed work with the existed literature.

Table 3. Comparison of the proposed antenna with the existed work

Ref No	Liu et al. [6]	Zhao et al. [7]	Behera et al. [8]	El Badawe et al. [9]	Zhang et al. [12]	Proposed Work
Patch						
Dimensions	60x60x1mm & 96mmx84mmx1mm	74cmx74cmx1mm	100x70x60mm	70mmx70mmx1mm	-	96mmx84mmx1mm
Substrates	FR4(4.4)	Rogers F4B (2.65)	RT/duroid 6006 (6.15)	Rogers substrate 10.2	Rogers R0310	FR4(4.4)
Operating frequency	2.4GHz	5.16GHz	2.45GHz	2.45GHz	-	2.4GHz
Gain	3.5dB	-	-	-	4.5dBi	8.0dBi
Efficiency	-	--	Antenna eff	Achieved maximum	-	93.5%

		>85.65%	of 62% harvesting efficiencies at four bands	
Front to Back ratio	-	-	-	113.5
Output voltage	1.98Volts			2.82volts
Any other results	-	35.1% Efficiency achieved at -10dB input power	Efficiency was achieved for 2mm and 6mm air gap	Achieved high efficiency with 113.5 of front to back ratio

7. CONCLUSION

The primary goal of this study is to design a metasurface antenna for use in RF energy harvesting applications in order to improve gain and bandwidth. It has been observed that from the open literature that a maximum gain of 3.5dBi and a bandwidth of 110MHz is achieved with a low output voltage.

The proposed antenna can be built with a dual substrate and a 10mm air gap, with FR4 as the dielectric material. On both substrates, the suggested antenna can be built with the metasurface plane. It was observed that the suggested antenna increased Gain 5dBi, i.e., from 3.5dBi to 8dBi, without effecting other parameters. The proposed antenna has been shown to exhibit low backward radiation, i.e., -13.1dB. The proposed antenna has fabricated using the FR4 substrates and measured using the network analyser. The entire design has done on the HFSS 19.2 and ADS 2020 software.

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