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Frequency Reconfigurable Antenna Using Metasurface of Rectangular Loop Unit Cells

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Abstarct:
In this paper design of a low-profile frequency reconfigurable metasurface (FRMS) antenna has been proposed. The proposed FRMS antenna consists of a simple rectangular patch antenna (source antenna) having circular ground plane of radius 20 mm and a circular metasurfaceof same radius. The metasurface is palced directly over the patch to make the FRMS antenna very compact with a total thickness of 3.048 mm. The metasurface consists of rectangular loop unit cells arranged uniformly along the vertical and horizontal directions. Simulation result shows that the antenna can be tuned by rotating the metasurface around the center of the patch antenna. Rotation of metasurface results a change in relative permittivity and relative permeability of the structure and the resonant frequency of the FRMS antenna. The proposed antenna has been designed on Ticonic RF-35 substrate with a dielectric constant of 3.5 and thickness of 1.524 mm. The antenna parameters like gain, return loss, radiation pattern and efficiency are analysed using HFSS. The proposed antenna resonantsfrom 4.5to 6 GHz. The antenna is suitable for various wireless communicationapplications such as WLAN band (5.180- 5.825 GHz), ISM band (5.725-5.875 GHz) and so on.

Keywords: Frequency reconfigurable antenna, unit cells, source antenna, HFSS.

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1. Introduction

Keeping in mind about the increased application and versatility of wireless communication network, researchers put more attention towards the development of reconfigurable antennas in the telecommunication field. The modification of the frequency band in the reconfigurable antenna can be achieved by two mechanisms which are electrical and mechanical. Band switching (discrete tuning) and continuous tuning are two categories of electrically reconfigurable antenna. Frequency reconfigurability can be achieved by using RF microelectromechanical systems (RF-MEMS [1], PIN diodes [2], varactors [3], and field-effect-transistors(FETs) [4]. These antennas require direct-current(DC) biasing circuits for the biasing of PIN diode or varactor diode or RF-MEMS or FETs.An electrical reconfigurable antenna relies on the DC electrical sources and electronic switching components which have an adverse effect on antenna operation and antenna performance depending on the reliability of the electronic components and DC sources. Mechanically reconfigurable antennas are characterized by movable parts to achieve frequency tuning. Mechanically reconfigurable antennas do not require complicated biasing circuits and exhibit good performance in dynamic environment [5]. Moreover, an actuator is a component or device which is responsible for monitoring a system. The use of actuator requires a bulky and expensive fabric or framework as it is very complicated and immerses more space. Moreover, the change in shape and size is most common and crucial problem for most mechanically tunable antennascombination.
Meta materials can be realized three-dimensionally by arranging electrically small scatterers or holes in a two-dimensional pattern on a surface. The two-dimensional equivalent of metamaterial is called metasurface(MS). Metasurfaces have the advantages of having less physical space and less-lossy structures [6]. With its compact planar configuration and cheap in price, MS has wide uses which reflects on the design of planar antennas. Result shows that the potential of a patch antenna could be intensified by placing a MS atop on it. The combination of the patch antenna and MS together called as MS antenna. The MS consists of rectangular loop unit cells which is used to tune the frequency and polarization of the antenna which remains linear same as the source antenna [8]. A FRMS antenna is designed using HFSS, where the patch antenna and MS are placed in

direct contact with each other by eliminating the air gap with them which leads to have a compact size, low cost, simple construction antenna and rectangular loop based structure unit cells used for the metasurface design. The rectangular structures are applied to design multiband antennas and the miniaturization of antennas as they have the feature of exhibiting a quasi-static resonant frequency at wave lengths that are much smaller than the guided wave length. The proposed FRMS antenna is designed to operate in the range of 4.75GHz to 6GHz using electromagnetic simulation tool HFSS software.

2. Metasurfaced Antenna Design

The proposed antenna consists of a source antenna and a metasurface as shown in the Figure 1. The metasurface is designed by a number of unit cells placed monotonously in the vertical and horizontal directions over a substrate. The unit cell is shown in Figure 2. In the designed FRMS antenna both the source antenna and metasurface have a circular shape of same measurements to achieve easy running and occupy same space. The patch antenna or source antenna is constructed over a double-sided substrate whereas the metasurface is fabricated on a single sided substrate. The metasurface is the combination of uniformly placed unit cells brought together in both horizontal and vertical directions. By rotating the metasurface around the centre of the patch antenna, frequency reconfigurability can be achieved. As the metasurface is symmetric in both horizontal and vertical direction, the maximum rotation angle without repetition is 90^0. To attain the low-profile erection and compressed size, the non-copper size of the metasurface is placed in direct contact with the radiator. The feed line of the antenna is characterized by 50Ω with a coaxial probe is fed to the feed line through the ground plane and substrate material. The dielectric substrate used here is Taconic RF-35(tm), having a thickness of 1.524mm and a relative permittivity of ε_r=3.5. The detailed geometrical dimensions of the proposed antenna are listed in Table 1.

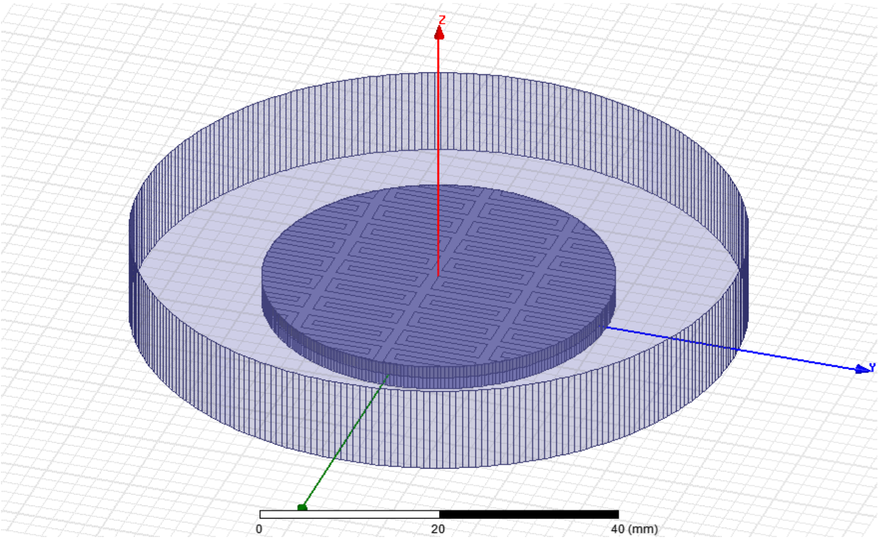

Figure1. FRMS antenna using HFSS

Table-1
All dimensions of unit cell are in mm units

a	b	w
10	3	0.5

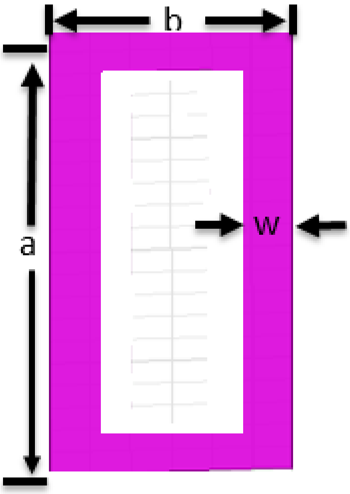

Figure2.Rectangular Loop Unit Cell

3. Analysis of Metasurfaced Antenna

The shape of the unit cells is symmetrical to both horizontal and vertical axis. The metasurface behaves similarly for equal angle of rotation either in clockwise or anticlockwise roation and the reponse repeats after every 90^0.The main aim of the recommended antenna is to achieve a change in FRMS by revolving the metasurface with respect to the source antenna. In case of FRMS antenna, the source or patch antenna which radiates linearly polarized signals that have fixed fundamental resonant frequency. Throughout the antenna analysis, a metasurface of infinite size is considered whereas the polarization direction of the linearly polarized plane waves making an angle θ with the unit cell along y direction. The HFSS software simulation tool is used to calculate and study about the S-parameters. The introduced rectangular loop unit cell is used to calculate the S_{11} and S_{21} parameters when the plane wave is incident normally on the substrate though the floquet port-1. If there is a rotation of electric field with respect to the y-axis, then the reflection coefficient and transmission coefficient will also change with the rotation of unit cell. The allowable frequency range to calculate the S-parameter ranges from 4-6GHz.By providing appropriate boundary conditions to the metasurface in HFSS, both S_{11} and S_{21} of a single unit cell are obtained at angles in complex form[7].
Since, the presumptuous MS has infinite size, periodic boundary has considered in HFSS simulation to evaluate the S_{11} and S_{21} parameters for the evaluation of equivalent impedance 'Z' and refractive index 'n' of the metasurface by using the following equations (1) and (2).

$$z = \pm\sqrt{\frac{(1+S_{11})^2 - S_{21}{}^2}{(1-S_{11})^2 - S_{21}{}^2}} \quad (1)$$

$$e^{ink_0 d} = X \pm i\sqrt{1-X^2} \quad (2)$$

Where $X = \frac{1-S_{11}{}^2 + S_{21}{}^2}{2S_{21}}$, k_0 is the wave number, d is the equivalent thickness of the metasurface.

We have

$$\Rightarrow t = e^{ink_0 d} = X \pm i\sqrt{1-X^2} \quad (3)$$

Taking natural logarithm (ln) on both sides of equation (3),

$$\ln(t) = ink_0 d$$

$$\Rightarrow n = \frac{\ln(t)}{ik_0 d} \quad (4)$$

Permeability of the metasurface = $\mu_r = nz$ and Permittivity of the metasurface= $\varepsilon_r = \frac{n}{z}$ can be obtained using equation (1) and (4).

The equivalent relative permeability μ_r is stable at approximately 1.

Analysis of the S-parameters of Unit Cell:
S-parameter Calculation:
1. Draw the structure with exact/ required specification.
2. Draw the boundary box with Z+ = 5 units and Z- =5 units.
3. Assign boundary to each face (Master-1, Master-2, Slave-1 and Slave-2).
4. Assign Excitation (Floquet port 1 & port-2)
5. Analysis set up.
6. Add frequency sweep

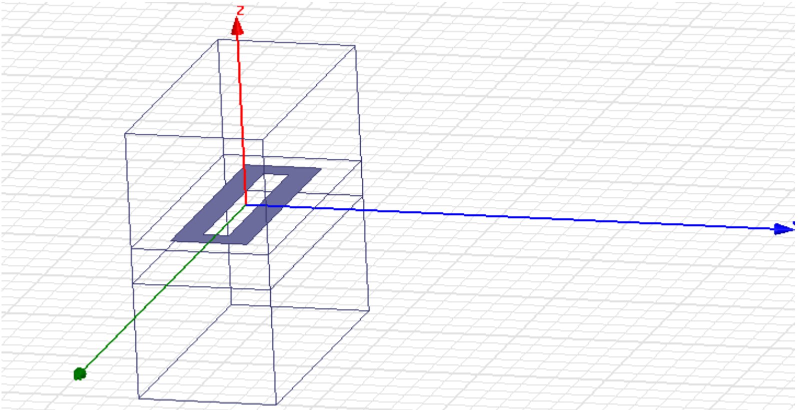

Figure 3.-Simulation model of unit cell using HFSS

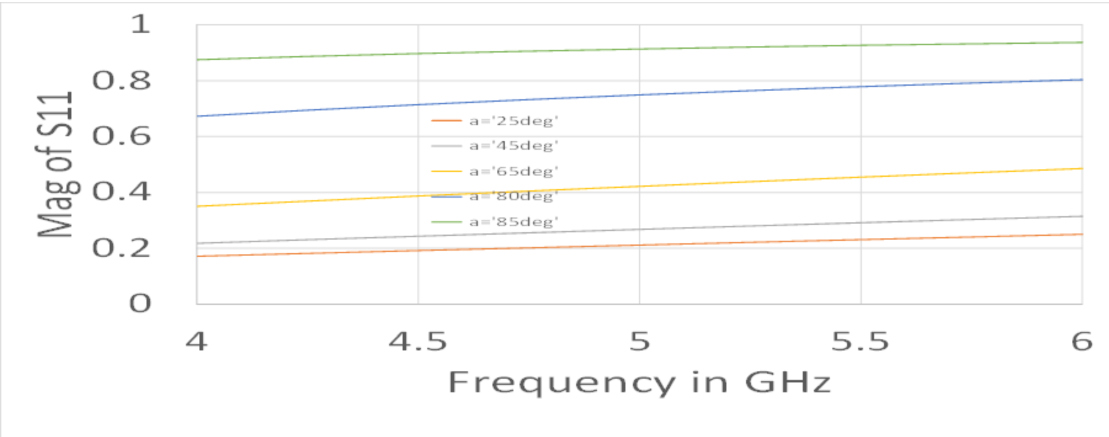

Figure 4 (a) Simulated S_{11} magnitude w.r.t frequency for different a=25^0,45^0,65^0,80^0, and 85^0 rotation of unit cell.

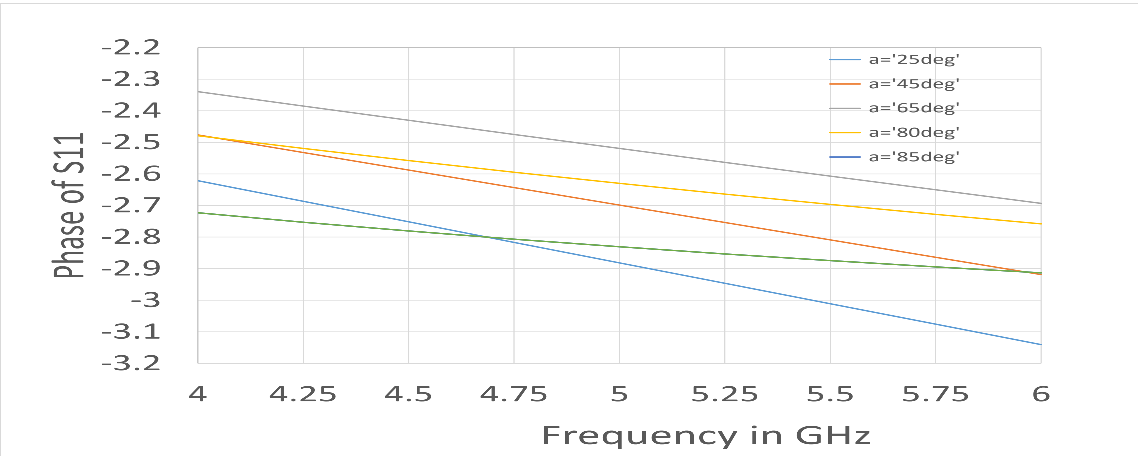

Figure 4(b) Simulated S_{11} phase in radian w.r.t frequency for different a=25^0,45^0,65^0,80^0 and 85^0 rotation unit cell

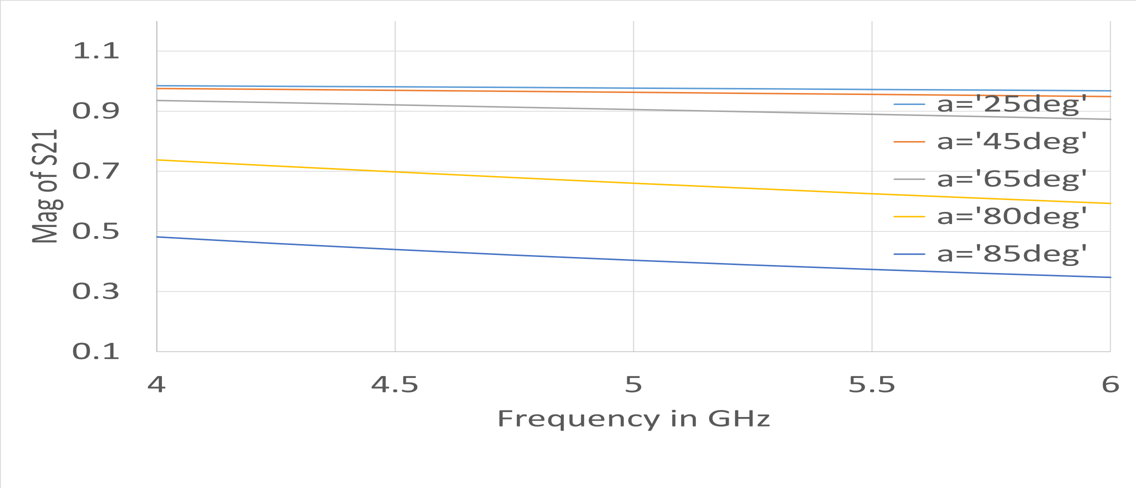

Figure 4 (c) Simulated S_{21} magnitude w.r.t frequency for different a=25^0,45^0,65^0,80^0, and 85^0 rotation of unit cell.

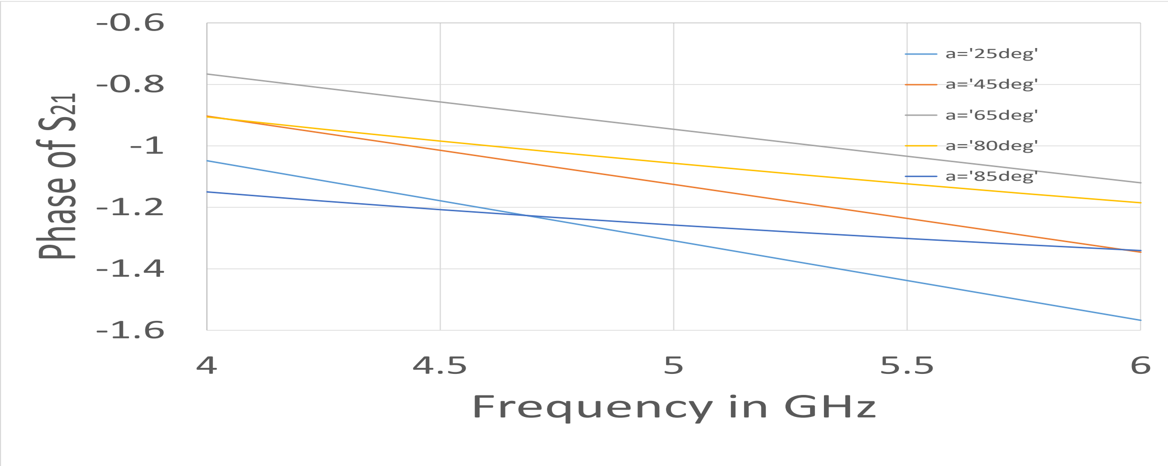

Figure 4(d) Simulated S_{21} phasein radian w.r.t frequency for different a=25^0,45^0,65^0,80^0, and 85^0 rotation of unit cell.

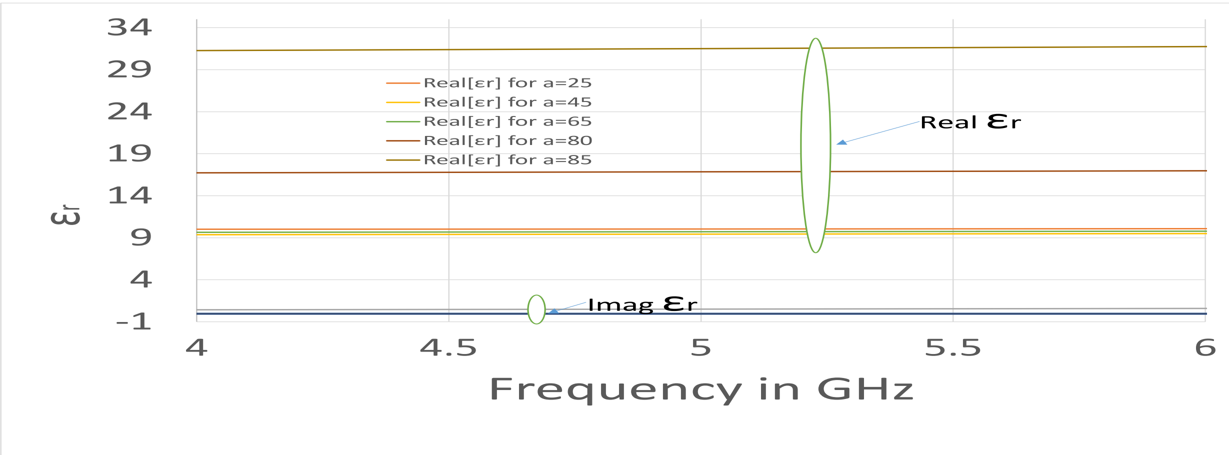

Figure 5. Calculated ε_rw.r.t frequency for different a=25^0,45^0,65^0,80^0, and 85^0 rotation of rectangular loop unit cell

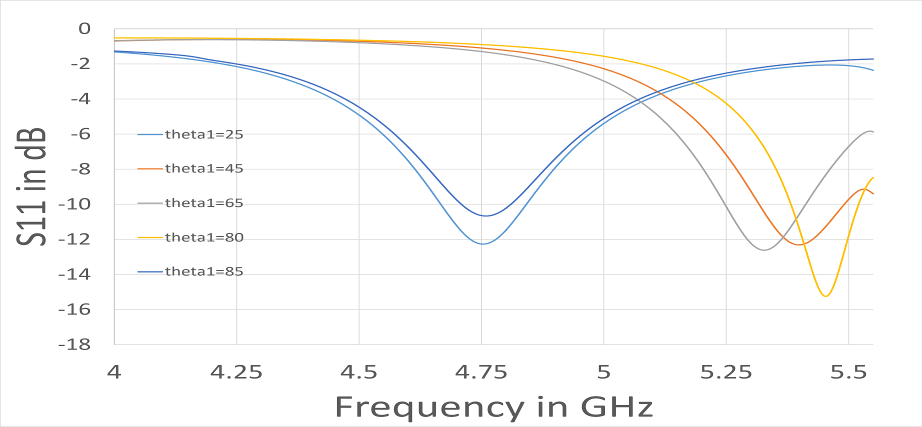

Figure 6. Simulated S_{11} of FRMS antenna at different rotation angles

Table 2.
Simulated Resonant Frequencies at Different MS Rotation Angles

Resonant Frequency(GHz)	4.77	5.07	5.27	5.51
Rotation Angle of Metasurface(MS)	10^0	35^0	55^0	80^0

4. Frequency Reconfigurability

Figure 3 shows the simulation model of unit cell using HFSS. The reflection coefficient S_{11} is obtained for the careful study of frequency reconfigurability of FRMS antenna. Figure 6 shows simulated S_{11} plot of the antenna with different rotation angles theta1.The resonant frequency of the antenna varied directly with a change in the rotation angle. With an increase in rotation angle from 10^0, 35^0,55^0, and $80^0$the resonant frequency increases which shifts from 4.77, 5.07, 5.27, and 5.51 GHz respectively as shown in Table 2. The S_{11} and S_{22} variation with respect to frequency is shown in Figure 4. Figure 5 shows ε_rw.r.t frequency obtained for different a = 25^0, 45^0, 65^0, 80^0, and 85^0 rotation of rectangular loop unit cell.

The determination of the periodicity of the unit cell is an important parameter in the design of metasurface. The unit cells have rectangular structure and are placed periodically along both the x-axis and y-axis in the FRMS antenna design. The unit cells have the lowest periodicity at theta1=0^0 and the highest periodicity at theta1=90^0 along the co-polarization direction of the patch antenna (y-axis). The rotation angle theta1 is directly proportional to the periodicity. With a change in theta1 from 0^0 to 90^0, the periodicity also varies from lowest to the highest, which corresponds to changing ε_r from the maximum to minimum.

5. Efficiency, Radiation Pattern and Gain

By performing the simulation, the antenna efficiency, radiation pattern and realized gain of the FRMS antenna at the resonant frequencies of 4.77, 5.07, 5.27 and 5.51 GHz have been discussed. The radiation pattern of FRMS antenna at 35^0 is shown in Figure 7. The radiation pattern is considered in far field region.The 3D-polar plot of proposed FRMS antenna is shown in Figure 8. Figure 9 shows the simulated efficiencies. In this case, the efficiency is the total efficiency which can be defined as the ratio of the radiated power from the antenna to the input power to the antenna. Result shows that the simulated efficiencies are above 88% at resonant frequencies as shown in the Figure 9. The feed efficiency of metasurface antenna can reach more than 95% by using planar or quasi-planar circularly symmetric sources [10].

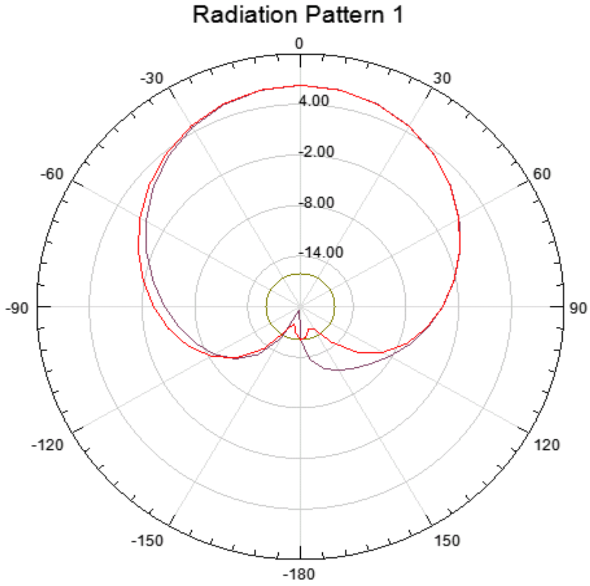

Figure 7. Radiation pattern at theta1=35^0 rotation of MS of FRMS antenna

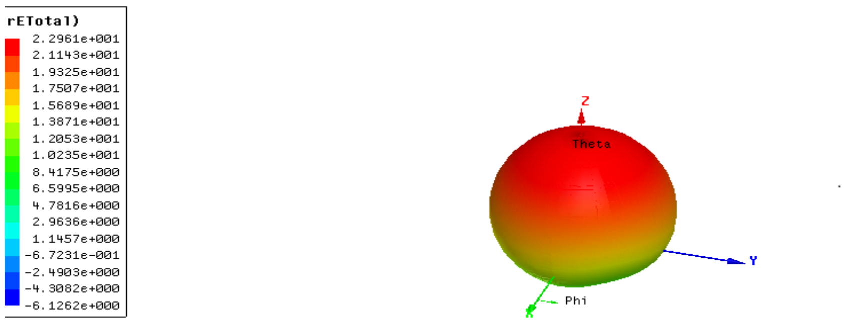

Figure 8. 3D Polar Plot of FRMS antenna

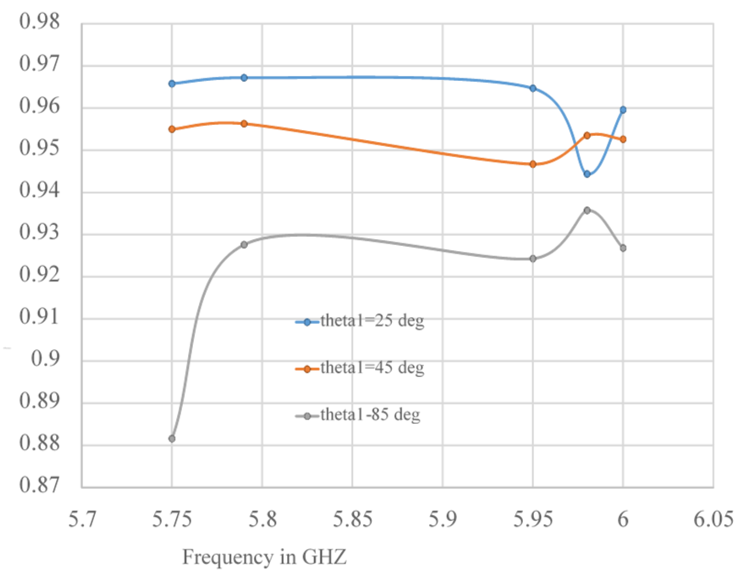

Figure 9. Simulated efficiencies at different rotation angles i.e. theta1=25^0,45^0,85^0

6. Conclusion

A compact frequency reconfigurable metasurface antenna for wireless application is presented.The antenna performance is analyzed in HFSS in terms of return loss,gain,radiation pattern and efficiency. The antenna can be tuned at different frequencies by rotating the meatsurface around the center source patch antenna. The advantages of this frequency reconfigurable antenna are wide tuning range from 4.75 GHz to 6 GHz.It is suitable for advanced for WLAN,ISM band to satisfy the diverse requirement without volume increment.

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