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Research Paper

Bandwidth and gain enhancement of RMPA using 'c' shaped metamaterial at THz

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Abstract

This paper elucidates antenna parameter optimization using C shaped metamaterial embedded in antenna substrate at high frequency (THz). Ansoft HFSS version 13 has been used to design and analyse the RMPA (Rectangular Microstrip Patch Antenna) with design frequency 2.75 THz and operating range of 2.15 THz to 3.35 THz having FR4 (εr = 4.4) as substrate material . Nicolson Ross Wier (NRW) method has been used to retrieve the material parameters from transmission and reflection coefficient. . Results were compared with MATLAB programming based on CAD formulas using equivalent circuit analysis of patch antenna. Finally, antenna parameters such as gain, bandwidth, and radiation pattern are investigated and presented in tables and response-graphs. The unique shape proposed in this paper, gives remarkable enhancement in bandwidth and antenna gain.

Keywords: *Antennas; Metamaterials (MTMs); Negative Index Material; Negative Refraction; RMPA; DNG; HFSS.*

1. Introduction

The past few years have been very eventful with respect to the evolution of the concept and implementation of 'left-handed materials (LHMs)'. 'Metamaterials' (MTMs) are engineered to modify the bulk permeability and/or permittivity of the medium [1]. It is realized by placing periodically, structures that alter the material parameters, with elements of size less than the wavelength of the incoming electromagnetic wave. It results in "meta" i.e. "altered" behaviour or behaviour unattainable by natural materials. Slight changes to a repeated unit cell can be used to tune the effective bulk material properties of a MTM, replacing the need to discover suitable materials for an application with the ability to design a structure for the desired effect. Examples of MTMs are single negative materials (SNG) like ε negative (ENG) which have effective negative permittivity and μ negative (MNG) which have effective negative permeability, and double negative materials (DNG).

It is worth recalling that negative values of permittivity are inherently bandlimited phenomena and such a condition can hold only at a certain frequency (accompanied with imaginary part of permittivity). Frequency for which real part of permittivity hits value ' -2' and infinity condition goes named as Frohlich frequency [2].Particle shape has effect on the value of negative permittivity corresponding to Frohlich resonance. The geometry of negative permittivity particle has a strong effect on its surface plasmonic properties.

A fresh approach to microwave and optical devices presented itself with the interesting breakthrough in the area of MTMs at high frequencies. The need of hour is to optimize the antenna parameters (gain , bandwidth , directivity) without altering its dimensions i.e. external control over antenna parameters using MTM . The software tool HFSS is used because it is a high performance full wave electromagnetic (EM) field simulator for arbitrary 3D volumetric passive device modeling. It integrates simulation, visualization, solid modeling, and automation in an easy to learn environment where solutions to 3D EM problems are quickly and accurately obtained [3].

This paper abridges the design of RMPA with resonant frequency 2.75 THz and operating frequency range of 2.15 THz to 3.35 THz having FR4 (εr = 4.4) as substrate material in Section 2. Section 3 gives parametric study using equivalent circuit analysis in MATLAB for patch antenna Section 4 describes MNG MTM (C shaped) having negative permeability in the same frequency range. Section 5 elucidates upon its application in antenna parameter optimization by embedding it inside the substrate. Section 6 concludes the trade offs in achieving parameter enhancement in RMPA with MNG material in substrate. Section 7 discusses the improvements that can be perceived in design of planar antennas using metamaterial at high frequencies along with challenges faced.

2. Designing of patch antenna in FEM based Ansoft HFSS software

RMPA i.e. Rectangular Microstrip Patch Antenna, as the name implies consists of a rectangular patch over a microstrip substrate. Its major disadvantage is relatively low-impedance bandwidth which limits the field of application of these antennas. Bandwidth of RMPA can be improved by several methods available in literature e.g. use of thick substrates, addition of parasitic patches. The implication of such methods will not just increase the complexity of system, but will have adverse effect on gain of the antenna. Also, such methods involve changes in the parameters of the designed antenna. This calls for a novel technique to increase the bandwidth of antenna without altering its parameters and without much affecting the antenna's radiation properties. Henceforth, we introduce the metamaterial based antennas.

Transmission Line model represents RMPA as two slots of width ,w, and height ,h, separated by transmission line of length ,l,. Thus, it is a non homogeneous structure made up pf two dielectrics i.e. substrate and air. This shows that substrate and air will have different phase velocity and the dominant mode of propagation will be quasi-TEM. Therefore effective permittivity ,εeff, comes into consideration. There is fringing effect at the edges of patch , due to which the patch appears to be longer. So, Leff, i.e. effective length is defined which is obtained by adding 2Δl (additional length Δl due to fringing on each end) to the length obtained by using mathematical design equations [4].Ground plane has length ,lg, and width, wg. The tangential components of electric field are in phase. Therefore, maximum radiated field is normal to the surface of the structure. However, normal components of the electric field at the two edges along the width out of phase. Hence, no radiation in broadside direction. As per transmission line model ground plane should be infinite in extent. Practically, ground plane is finite with size greater than the patch dimensions by approximately six times the substrate thickness.

The operating frequency range of the designed antenna is 2.15THz to 3.35 THz with centre frequency 2.75THz. The substrate is FR4 (εr =4.4).

Constructional details are shown in Table 1.

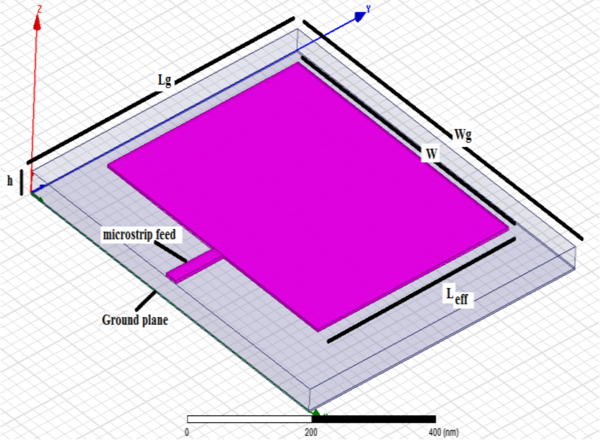


Fig. 1: Rectangular Microstrip Patch Antenna

Table 1: Design Parameters of RMPA

Frequency range	2.15-3.35THz
Center frequency	2.75THz
ε_r	4.4
ε_{eff}	4.07
h	1.5µm
w	33µm
L_{eff}	27µm
ΔL	0.69µm
L	25.6µm
L_g	34.6µm
W_g	42µm

Using design parameters RMPA has been designed in Ansoft HFSS as shown in Figure2.

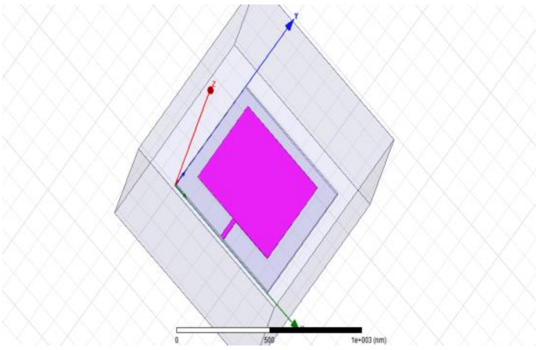
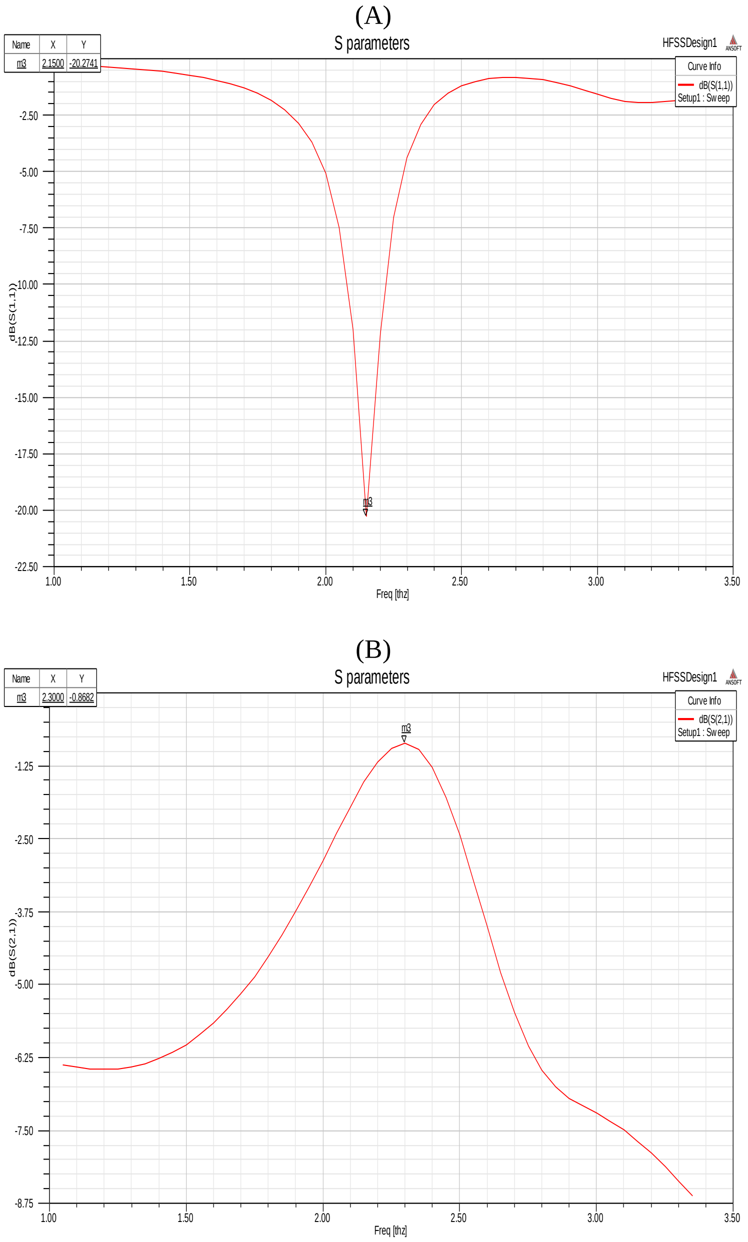


Fig. 2: RMPA Design in HFSS

RMPA has been simulated in HFSS. Figure 3 shows the simulation results where S11 is return loss or reflection coefficient and S21 is the gain of the antenna .



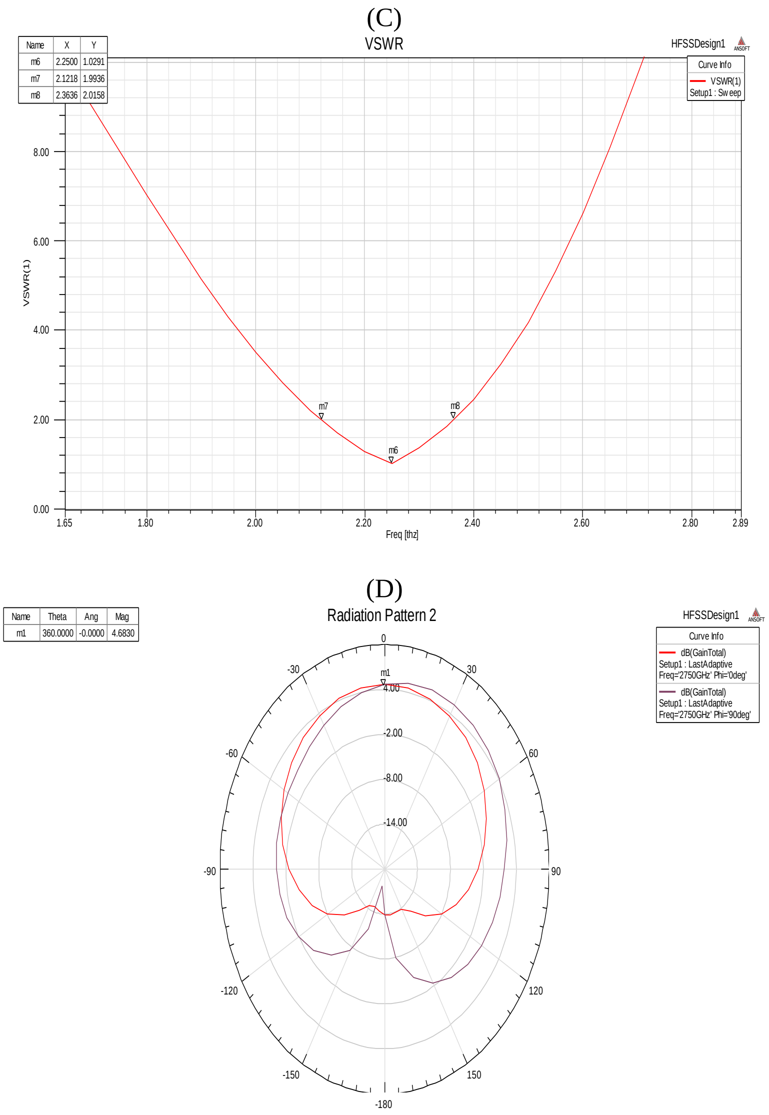


Fig. 3: A) Return Loss. B) Gain. C) VSWR. D) Radiation Pattern in E and H Plane of RMPA

Simulation results have been shown in Table 2.

Table 2: Simulation Results of RMPA at 2.25 THz

Parameters	RMPA
S11 (dB)	-20.2741
S21 (dB)	-1.1565
VSWR	1.0291
Bandwidth (THz)	0.2418
H plane gain in dB	4.6830
E plane gain in dB	4.6830
Peak directivity(dB)	5.5068
Front to back lobe ratio(dB)	16.875

It can be seen that S11 is crossing 10 dB line and VSWR is less than 2 .Bandwidth is 0.2418 THz , which is range of frequencies with VSWR < 2.

3. Designing of patch antenna in MATLAB

Microstrip antennas (often called patch antennas) are widely used in the microwave frequency region because of their simplicity and compatibility with printed-circuit technology, making them easy to manufacture either as stand-alone elements or as elements of arrays [5].The parametric study using the CAD formulas are fairly accurate for thin substrates and illustrate the basic principles. For thin substrates the CAD formulas may even be accurate enough for final design purposes. For thicker substrates these formulas can still be used for initial design work, with full-wave simulation tools used to complete the final design. Using CAD formulas and programming in MATLAB by parametric study, following results have been obtained in Figure 4.

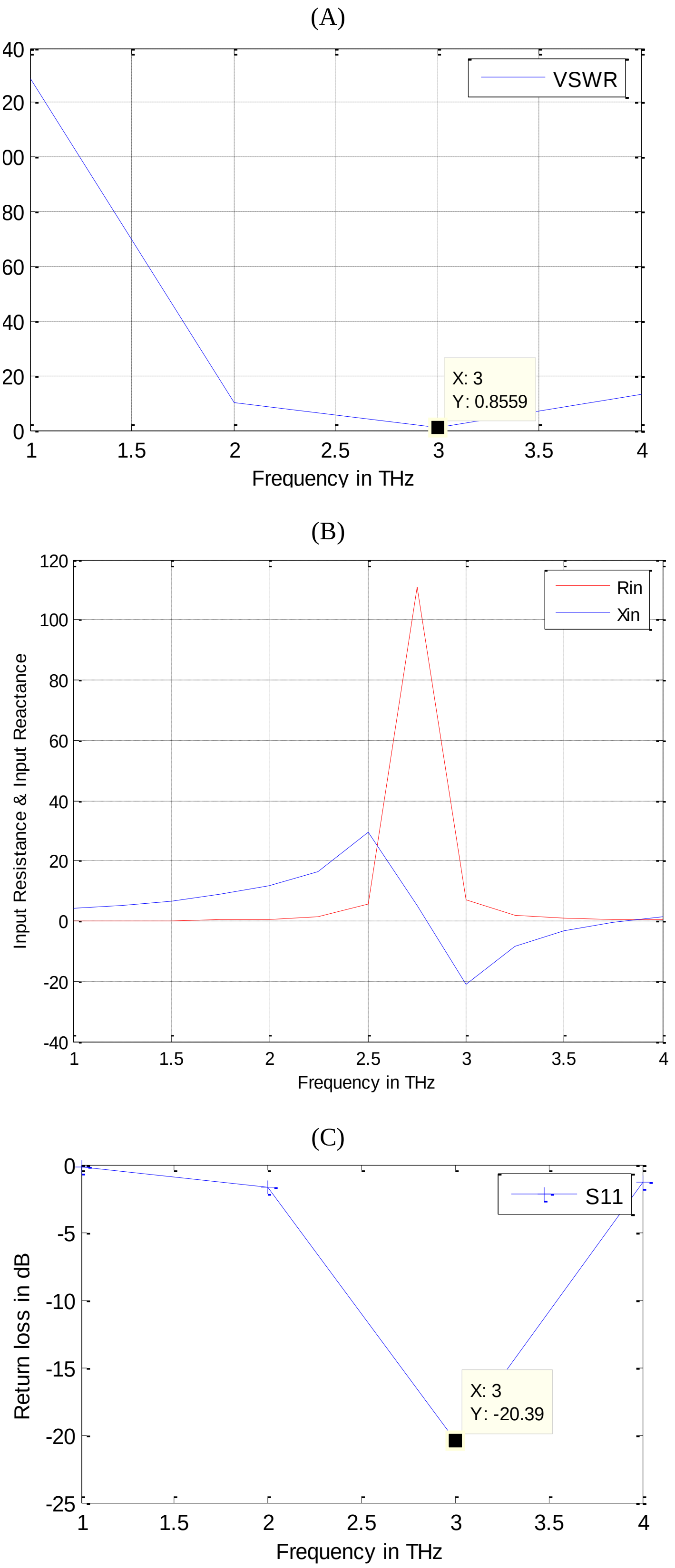


Fig. 4: RMPA for ‘4seg’ Shaped MTM: A) VSWR. B) Input Impedance vs. Frequency. C) Return Loss.

It can be observed that using CAD formulas for microstrip patch antenna in MATLAB, we can initially plot the curve between input impedance and frequency. Thereby, we can obtain S11 and VSWR by applying the formulas, Reflection coefficient is ratio of (Zin-Zo)/(Zin+Zo) and VSWR is ratio of (1+abs(reflection coefficient))/(1-abs(reflection coefficient)).It can be seen that results are well in coherence with that obtained from FEM simulation.

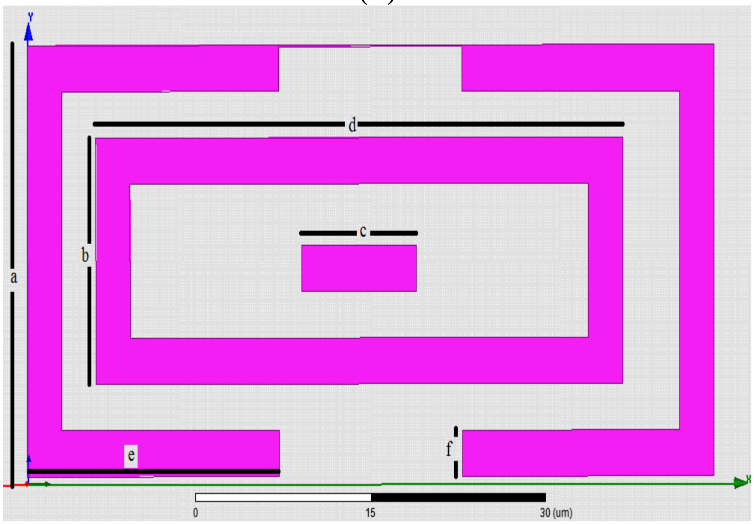
4. ‘C’ shaped metamaterial

In 1968, Russian scientist Veselago [6] postulated a negative material and theoretically proved the phenomenon that a uniform plane-wave followed the left hand rule in a medium with negative permittivity (ε) and negative permeability (μ). The first work in this direction was by Pendry. He created a medium consisting of thin wires arranged in a periodic array [7]. These wires acted as a plasma medium, whereby ε varies with frequency, Pendry next achieved a negative μ with a periodic array of metallic loops called Split Ring Resonators [8]. In a medium composed of these rings the permeability, μ, varied with frequency, and could become negative. In 1999, Smith combined the rod and ring materials to finally produce a material with simultaneously negative ε and μ, a left-handed material [9]. The wire strips affect the ε and the split-ring resonators (SRRs) alter the μ of the medium thus giving a frequency dependent negative material with both the parameters negative. The wire medium and the SRRs have certain frequency dependence. The rod gives negative permittivity, ε, and ring material creates a negative permeability, μ , this combined rod and ring material gives negative index of refraction.

C-shaped metamaterial has been proposed having bianisotropy. It behaves as DNG i.e. Double Negative Group. Such materials have negative permittivity and negative permeability in the same frequency region. Thus having negative refraction in the same [10],[11]. The parameter retrieval i.e. parameter extraction using S parameters [12] has been followed using NRW approach to observe the negative refraction region of MTM. The constructional details along with the curve showing negative refraction are as under.

It is constructionally very simple, consists of a C shaped conductor, such that it looks like two opposite Cs surrounding two rectangular strips as shown in Figure 5(a) [13].Parameters of the proposed metamaterials are shown in figure 5 (b).

(A)



(B)

Parameter	Value (in μm)
a	28
b	16
c	10
d	46
e	22
f	3

Fig. 5: C Shaped MTM. A) Unit Cell Designed In HFSS. B) Constructional Details.

Nicolson Ross Wier method has been used to calculate the material properties from transmission and reflection coefficients. It can be observed as in figure 6 that region of negative permeability extends from 2.1461THz to around 3.35THz.

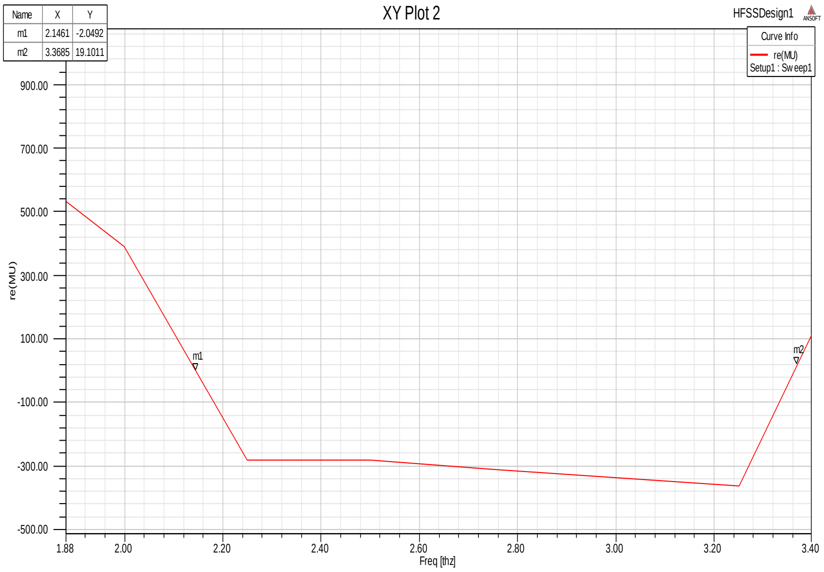


Fig. 6: Resonance in Permeability from 2.1461 THz to 3.35 THz

5. Designing of ‘C’ shaped metamaterial embedded patch antenna

Antenna is characterized by different parameters e.g. gain, bandwidth, VSWR, 3 dB beamwidth in E,H plane, return loss. These parameters have been obtained for RMPA as in table 2 using HFSS. Parameter optimization is done by embedding the proposed C shaped metamaterial in array of 3 elements spaced at 0.4μm from each other such that the left and right corner of MTM are superimposed on the RMPA radiating slots and center of the 2nd element coincides with the center of the antenna substrate just below the patch as shown in Figure 7.

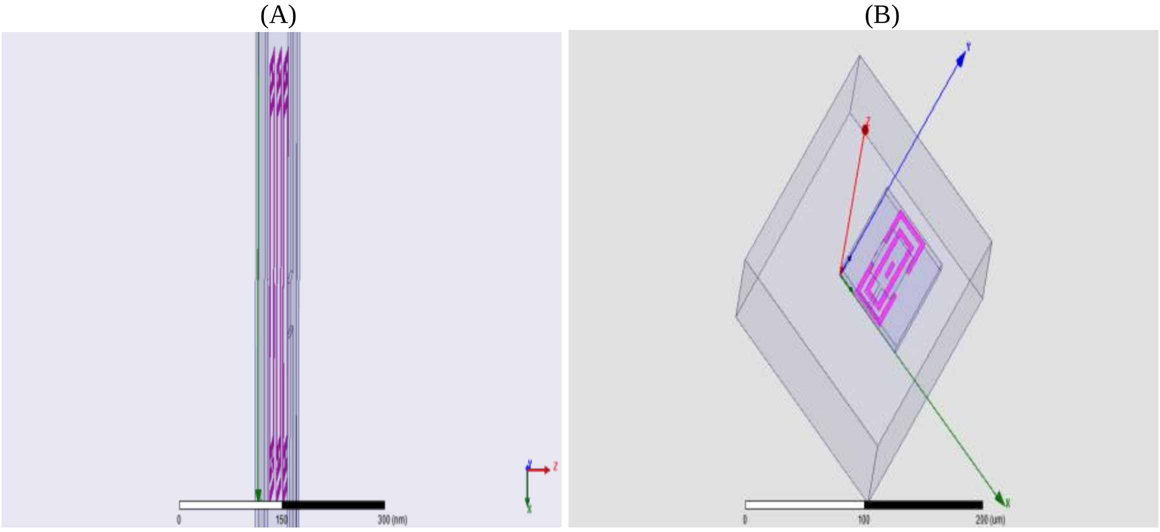


Fig. 7: A) B) Embedding C-Shaped MTM inside RMPA Substrate

Simulation results for C-shaped MTM inside RMPA substrate are shown in Figure 8.

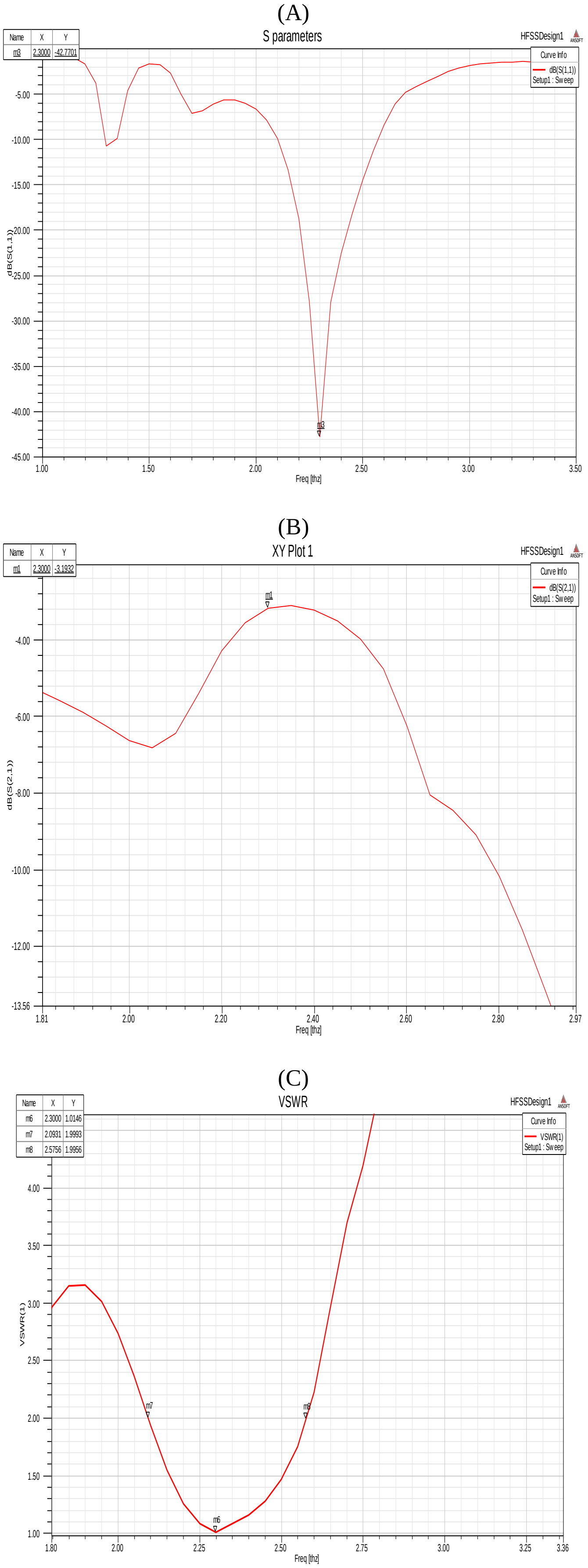


Fig. 8: A) Return Loss. B) Gain. C) VSWR of ‘C’ Shaped Metamaterial Embedded Patch Antenna

Table 3 gives the obtained simulated values of parameters and comparison of C-shaped MTM RMPA with RMPA without MTM.

Table 3: Simulation and Comparison Results of C-Shaped MTM Embedded in RMPA Substrate

ANTENNA/ Parameters	RMPA	RMPA with C-shaped MTM	Improvement (approx)
S11 (dB)	-20.2741	-42.7701	5%
S21 (dB)	-1.1565	-3.1932	176%
VSWR	1.0291	1.0146	1.5%
Bandwidth (in THz)	0.2418	.4825	99.55%
Front to back lobe ratio(dB)	16.875	15.268	-9%

6. Trade-Offs

Upon designing and analyzing proposed MTM inside RMPA substrate we obtain results as in Table 3. It can be seen that bandwidth almost doubles with C-shaped MTM. VSWR improves up to 1.5%. Improvement in S11 i.e. return loss is 5%. However, gain (S21) improves by 176%. Trade off lies in improvement of above antenna parameters over front to back lobe ratio as it is worsened by 9%. The coherence between equivalent circuit analysis using parametric study by applying CAD formulas in MATLAB and Finite Element Method technique in HFSS has been observed.

7. Challenges

Antennas have been built taking metamaterial inside substrate. Their performance and design have been defined from response functions. This area of research provides a great challenge in assimilating different peoples, from various interdisciplinary fields, at different research levels, from mathematical to designing, from fabrication to system-oriented simulations. All the proposed designs of unit cell give insight into a search for new geometries and materials. This further leads to problem of finding required accuracy or authentication of the designed unit cell by some numerical simulation supported by various electromagnetic solvers.

Thus, the entire process of developing a new metamaterial, to be used in antenna, involves tradeoffs from purely mathematical (theoretical) to fabrication (simulation).By analysing any unit cell by electromagnetic solvers, we can easily determine its S-parameters, thereby, its reflection and transmission coefficients. Using parameter extraction, medium parameters can be extracted. But no technique has been developed when ε and μ are tensors, also to solve Maxwell’s equation in fully anisotropic media. Using MTMs in antennas in substrate, we have been able to achieve: increase in antenna gain, decrease in HPBW (half power bandwidth) , improvement in bandwidth. The major challenge is to determine whether these promises of MTMs are consistent with the theoretical limits of gain, Q, bandwidth and directivity, etc., achievable by antennas and to reduce side lobes or backlobes so that directivity can be enhanced.

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