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Behaviour of Metamaterial Antenna under the Influence of Various Substrates

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Abstract— **In this paper, a comparative analysis and study of parametric improvement in conventional antenna in the form of Microstrip Patch Antenna using an Electromagnetic Band Gap Structures have been done. Two different configurations Rogers RT Duroid 5870 & FR-4 substrate with and without EBG are studied along with the proposed comparative analysis. The EBG structures are directly etched/ as embedded in the ground plane without disturbing on its radiating patch. These EBG structures are constituent parts of Metamaterials as a virtue of which, the performances of parameters such as: Bandwidth, Directivity, Efficiency, Gain and Power Pattern are keen improved which is very much essential for the applications based on the Wi-Fi and ISM Bands as the counterpart for the Wireless Communication Domain. With perspectives of theoretical aspects of simulations, L-C matching and parametric optimization with the help of the Genetic Algorithm, so as to support out its existence.**

Index Terms— ***EBG Structures, Genetic Algorithm, Gain Enhancement, L-C Matching, Metamaterials, Microstrip Patch Antenna's, Scattering Parameters Extraction.***

I. INTRODUCTION

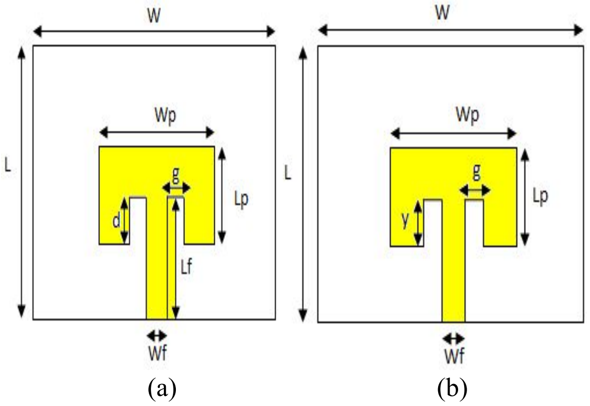
In the current era of communication, antenna's play a major role in determining the success of application. Without it, the major sanctions can't be achieved out. Microstrip patch antenna is the special types of antenna's which consisting of conducting patch of any planar or non-planar geometry on one side of the dielectric substrate with a ground plane on the very next side. With advent of this, they raise in benefits like dual and circular polarization, dual frequency operation, frequency agility, broadband width, feedline flexibility, beam scanning followed by omnidirectional patterning [1].

EBG structures are the constituent parts of metamaterials which is generally defined as macroscopic composites having synthetic, three-dimensional and periodic cellular architecture designed to produce out the optimized combinations which are not available in the nature [2]. In another sense, they are often realized as the periodical arrangements of the dielectric materials with presence of metallic conductors which suitably highlights the main objective of working. These features as always, taken into consideration in designing the prospectives of antennas.

In this proposed work, the performance of various antenna parameters of a rectangular microstrip patch antenna is keen to be upgraded leaving behind traditional problems. As in the earliest, scope of working was limited to certain acceptance of realities [3] [4] but in this case, the authors are successful in carrying major improvements in various antenna parameters: Bandwidth, Directivity, Efficiency, Gain & Power Handling Capacity. All of these are possible by use of EBG structures acting as the matching networks, along with the association of microstrip patch antenna [5]. By using, the primary objectives of the present work are well illustrated out, citing for the fulfillment of at par specifications, as mainly required for the modern applications. It is much more application oriented that describing major functionalities in the domain of Wi-Fi Bands & ISM Applications with proper take up of optimizer called as Genetic Algorithm.

II. ANTENNA AND EBG STRUCTURE DESIGN

In the present paper, two different materials have been used to design a rectangular microstrip patch antenna with inset feed with the resonant frequencies of 2.45 GHz aiming for an IEEE 802.11 b/g/n applications [8] and the next 2.4 GHz for the wireless fidelity (Wi-Fi) applications [10] as shown in Fig. 1(a) & Fig. 1(b) and they are designed by using standard mathematical formulations to calculate various constructional parameters. In order to brief them out, two configurations of the different instances are taken into the considerations, as configuration-I and configuration-II with all constructional parameters as shown in the Table I respectively.



(a) (b)

Fig.1 (a) Structure of a Rectangular Microstrip Patch Antenna using Rogers RT Duroid 5870 substrate and (b) Structure of a Rectangular Microstrip Patch Antenna using FR-4. It is to be noted that mathematical formulation is same for both the cases, but their values are calculated individually. They always followed the procedures of standard mathematical formulation.

The design procedures [6] involve calculation of:

1. Calculation of Width
2. Calculation of Effective Dielectric Constant

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3. Calculation of Effective Length
4. Calculation of Length Extension
5. Calculation of Actual Length of Patch
6. Calculation of Ground Dimensions

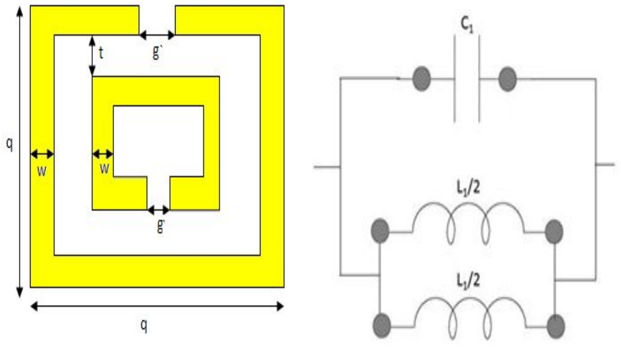
TABLE-I
CONSTRUCTIONAL PARAMETERS OF BOTH CONFIGURATIONS

For Configuration-I	
Parameters	Dimensional Values
ε_r	2.33
W	94 mm
L	78 mm
Wp	47 mm
Lp	39 mm
tm	0.035 mm
h	0.787 mm
Wf	2.3 mm
Lf	32 mm
d	12.7 mm
g	1
Substrate	Rogers RT Duroid 5870
For Configuration-II	
ε_r	4.4
W	76 mm
L	58 mm
Wp	38 mm
Lp	29 mm
y	8.85 mm
g	1 mm
Wf	3.137 mm
tm	0.035 mm
hs	1.6 mm
Substrate	FR-4

After both the configurations by using different substrates have been created out, EBG structures as constituent part of metamaterials in form of square split ring resonators (SSRR) come into the arena. These are mainly formed on, by keeping fundamental ideology that if it exhibits negative permeability and negative permittivity, then that can be treated/considered as a trademark when we go the case of simulations and when we do the analysis by using concepts of the Inverse Problem: Extraction of the Material Parameters [7] [9] [13], we also get identifying outcomes. The EM modeling consists of:

1. Design a Unit Cell
2. Extract Effective Parameters
3. Model with Bulk Parameters
4. Perform Microscopic Inclusions

Along with these are further investigated out by using any full wave simulator as CST-MWS [7] where their foremost on behvaiour can be extracted to meet standard requirements. All major structures & dimensions of square split ring resonators (SSRR) [14] which is in the form of EBG structures as given in Fig. 2 (a) with the circuit implementation in Fig. 2 (b) & in Table II respectively.



(a) (b)

Fig.2 (a) Electromagnetic Band Gap (EBG) Structure in the form of Square Split Ring Resonator where the basic form is modified and the orientation is changed so as to suit the performance of Metamaterial Antenna & in the Fig. 2 (b) Circuit Implementation of Square Split Ring Resonator (SSRR).

TABLE-II
CONSTRUCTIONAL PARAMETERS OF EBG STRUCTURES

Parameters	Dimensional Values (in mm)
g`	0.3
hs	0.25
q	2.2
ls	0.14
t	1.5
tm	0.035
w	0.2

With respect to above theoretical formulations, another set of methods are also used which effectively provides concepts for computational benefits of the metamaterials. They follow the steps such as:

1. Initialize Maxwell's Equation
2. Constitutive Parameters
3. Reflection Coefficient and Propagation Factor
4. Snell's and Fresnel's Formulas
5. Testing of LHM and RHM

The various approaches for this case, that includes mainly the Nicholson-Ross-Weir Method, Lorentz Drude Model and the last Kramer's-Kronig Relations which stand behind them [9]. With the virtue of it, the major possibilities of evaluation are easily done.

$$Z=\text{sqrt of } \{\{(1+S_{11})^2-S_{21}\} / \{(1-S_{11})^2-S_{21}\}\} \quad (1)$$

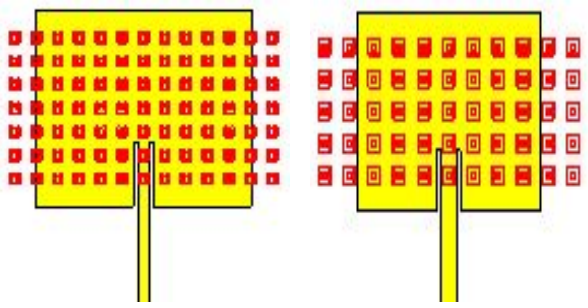
$$S_{11}= R^2_{01}\,(1-e^{-i2nkd})\,/1- R^2_{01}\,(1-e^{-i2nkd}) \quad (2)$$

$$S_{21}= 1- R^{2}_{01} (1-e^{-i2nkd}) / 1- R^{2}_{01} e^{-i2nkd} \quad (3)$$

$$\varepsilon= n/Z \quad (4)$$

$$\mu= nZ \quad (5)$$

In the last part, metamaterial antenna is evolved out as it by incorporating out the EBG structures in the form of square split ring resonator (SSRR) in the ground plane of rectangular microstrip patch antenna as shown in Fig. 3 (a) and (b) for configuration-I & configuration-II respectively. It should be noted that the dimensions of the conventional antenna's are reduced out, which ultimately provided an solution related to the size of the antenna. In lieu of this, they acted as matching networks [5] which is generally aimed for upgrading all the major performances of various antenna parameters.

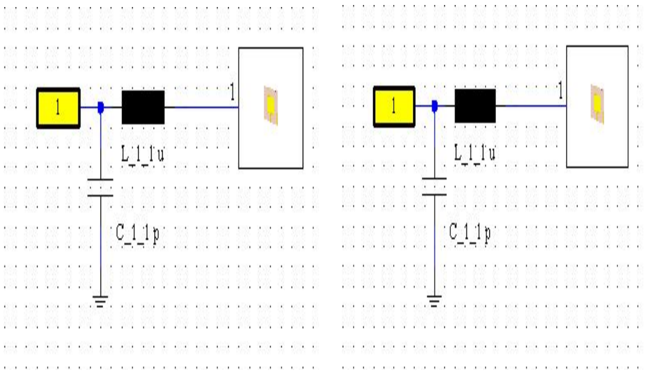


(a) (b)

Fig.3 (a) Metamaterial Antenna for the Configuration-I with Rogers RT Duroid 5870 substrate and in the Fig.3 (b) Metamaterial Antenna for the Configuration-II with FR-4 substrate. As Electromagnetic Band Gap (EBG) Structures or Metamaterials are directly etched in the ground plane of the Conventional Antenna.

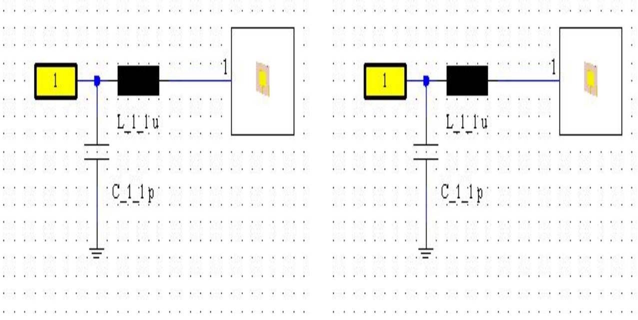
III. RESULTS, DISCUSSION AND ANALYSIS

After establishing out the theoretical implementations, we would look forward in extracting the performances of various parameters with the help of CST-MWS, which is based on the principles of FDTD method and takes into account all the aspects of Maxwell's Equation. Here the antenna parameters include out Reflection Coefficient from where Bandwidth can be determined out with the follow up from Directivity, Gain, Efficiency & Power Pattern. With this the main highlights are briefed as in the form of comparative analysis. After this, L-C matching is carried out for both the configuration-I as in Fig. 4 (a), (b) and also for configuration-II in Fig. 5(a), (b).



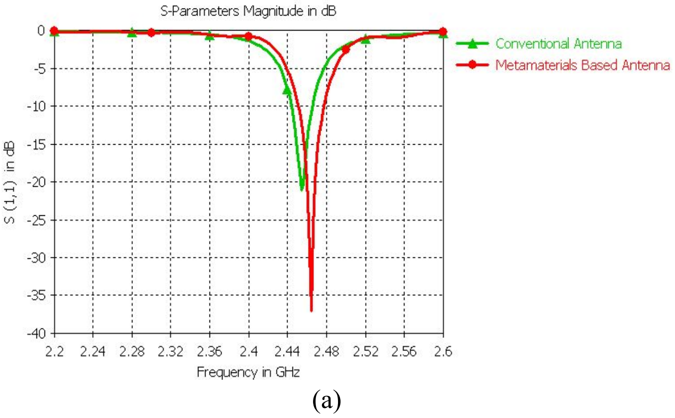
(a) (b)

Fig.4 (a) L-C Matching Circuit for Conventional Antenna of Configuration-I with L=0.598 nH and C=0.446 pF and in Fig.4 (b) L-C Matching Circuit for Metamaterial Antenna of Configuration-I with L=2.69 nH and C=1.51 pF.

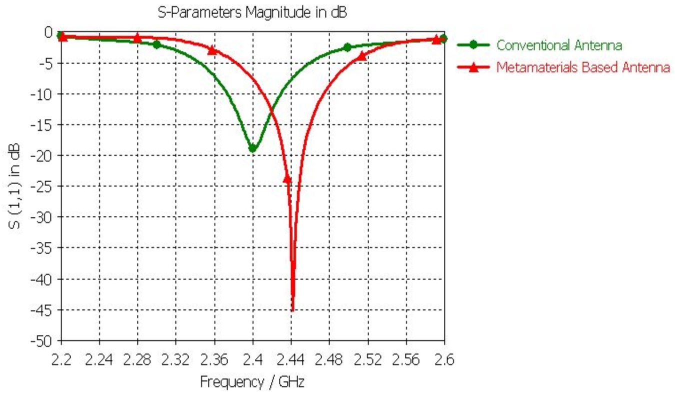


(a) (b)

Fig.5 (a) L-C Matching Circuit of Conventional Antenna of Configuration-II with L=2.12 nH and C=1.28 pF and in the Fig.5 (b) L-C Matching Circuit for Metamaterial Antenna of Configuration-I I with L=2.13 nH and C=1.23 pF



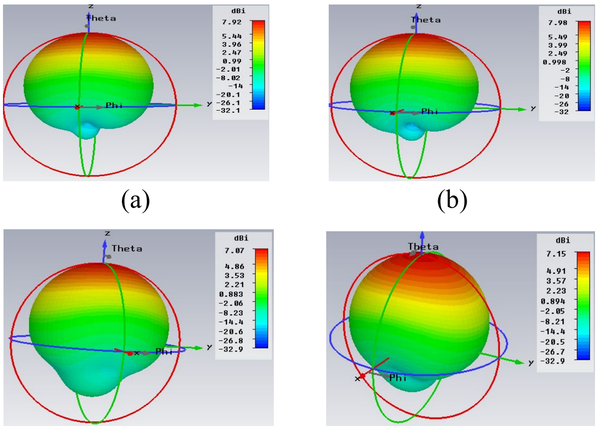
(a)



(b)

Fig.6 (a) Reflection Coefficient of Configuration-I with Rogers RT Duroid 5870 substrate, Fig.6 (b) Reflection Coefficient of Configuration-II with FR-4 substrate. From above the Bandwidth can be effectively calculated by taking the differences between the Highest and Lowest Frequencies with -10 dB as a standard reference.

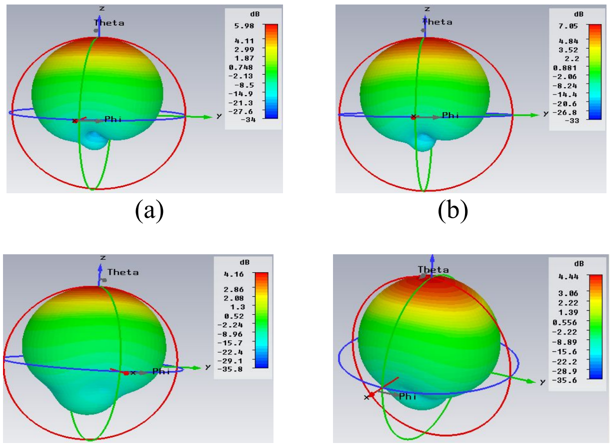
With consideration of an early establishment in Fig. 6 (a), (b), the Directivity factor claims out an essential in case of antenna performance. The separate briefings have been done in the case for both the two configurations shown in Figure 7 (a), (b) and Fig.7 (c), (d).As the designed prototypes must behave well with respect to theoretical findings, but it needs to know does the prototype is in synchronization with the needs of modern applications as in wireless communication domain. In to nullify them, Gain is considered to be the most important phase for antenna, essentially justifying its need. These are all briefed as shown in Fig. 8 (a), (b) in case of configuration-I & in Fig. 8 (c), (d) in case of configuration-II respectively.



(a) (b)

(c) (d)

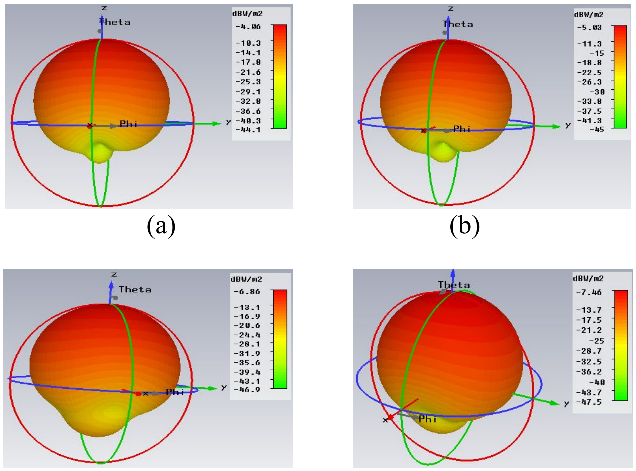
Fig.7 (a), Fig.7 (b) 3D Plot of Directivity for Configuration-I: Conventional and Metamaterial Antenna. Fig.7 (c), Fig.7 (d) 3D Plot of the Directivity for Configuration-II: Conventional Antenna and Metamaterial Antenna.



(a) (b)

(c) (d)

Fig.8 (a) and Fig.8 (b) 3D Plot of Gain for the Configuration-I: Conventional and Metamaterial Antenna. Fig.8 (c) and Fig.8 (d) 3D Plot of the Gain for the Configuration-II: Conventional and Metamaterial Antenna.

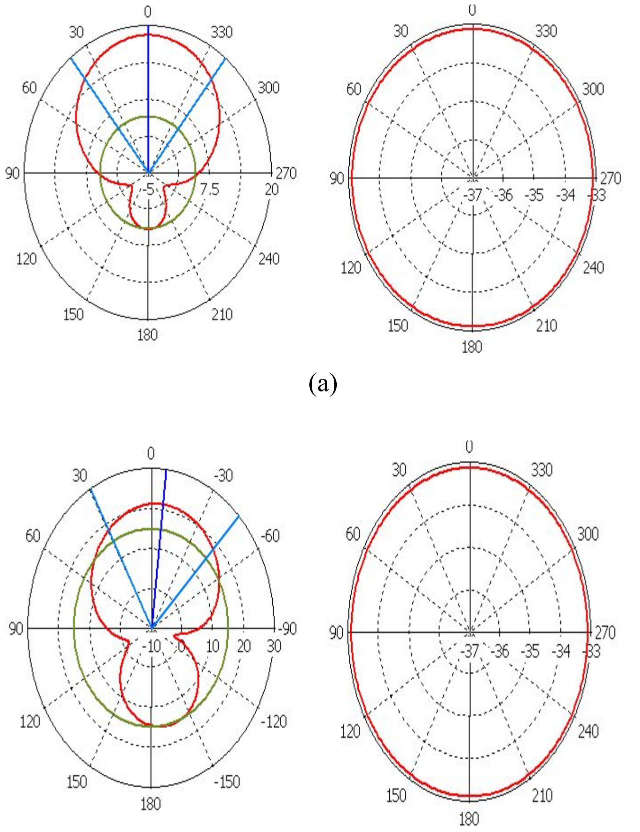


(a) (b)

(c) (d)

Fig.9 (a) and (b) 3D Plot of Power Pattern of Configuration-I: Conventional & Metamaterial Antenna. Fig.9 (c) and (d) 3D Plot of the Power Pattern of Configuration-II: Conventional and Metamaterial Antenna. It shows on the Power Handling Capability.

As the fulfillment of an intrinsic need for applications in wireless communication, the existence of prototypes are also depends upon the factors like as proper distribution of power pattern or power handling capability which plays an important role. This is extensively briefed out in Figure 9 (a), (b) in case of configuration-I with a separate way for configuration-II in Figure 9 (c), (d). In all the prospectives these are needed to be countered differently with the proper acquisition for the best possible display of performance of antenna parameters.



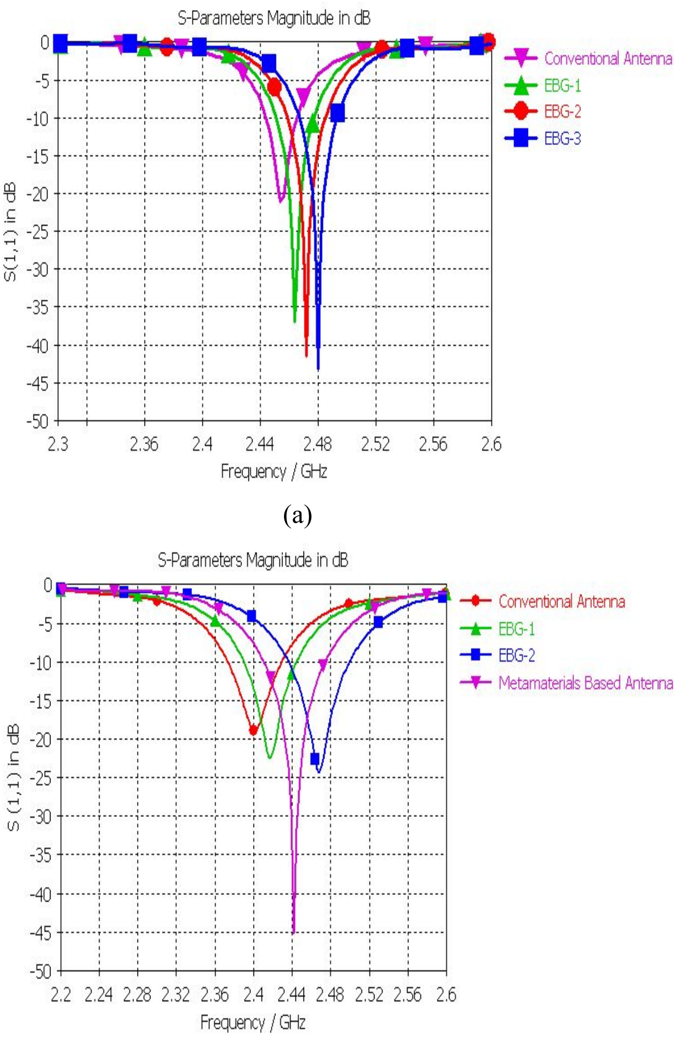
(a)

(b)

Fig.10 (a) Metamaterial Antenna of Configuration-I with Rogers RT Duroid 5870 substrate. Fig.10 (b) Metamaterial Antenna of Configuration-II with FR-4 substrate. Omnidirectional Pattern for E-Plane & Bidirectional Pattern for H-Plane.

After this, there is a scope of the parametric optimization as it shows out a series of simulations where one or more case of parameters are varied to investigate the sensitivity of solution to the parameters as we had done in the case of varying the EBG structures and noted their impact on antenna's as shown in Fig. 10 (a), (b) for both configuration-I & configuration-II. The varied parameters in relation to their dimensions are as follows:

1. Width of the Rings
2. Length of the Rings
3. Gap Between Rings
4. Slit Width
5. Positioning of EBG Structures
6. Number of EBG Structures



(a)

(b)

Fig.11 (a), (b) Parametric Study of the Electromagnetic Band Gap Structures where the primary parameters such as Width of Rings, Length of Rings are varied & their impact was noted on the Metamaterial Antenna where it was bring comparison with Conventional Antenna of both Configurations.

As it is clear from the traditional behavior of an microstrip patch antenna as it is lagging behind with the basic antenna parameters [1], but problems as complemented & enhanced by using the EBG structures. All the highlights are briefed in form of comparative analysis as shown in Table III, Table IV Table V and Table VI respectively.

TABLE-III
PERFORMANCE ANALYSIS OF ROGERS RT DUROID 5870 ANTENNA PARAMETERS

Parameters	CA (2.45 GHz)	Configuration-I (2.46 GHz)	Change
Bandwidth	21.2MHz	26.2MHz	+23.10%
Directivity	7.900dBi	7.989dBi	+1.126%
Efficiency	2.025dB	3.065dB	+51.35%
Gain	5.983dBi	7.145dBi	+19.42%
Power	4.063dBW/m^2	5.034dBW/m^2	+23.89%
Ref. Coefficient	-21.07 dB	-36.99 dB	+75.55%
Size	94X78mm^2	84X75mm^2	-16.38%

TABLE-IV
PEFORMANCE ANALYSIS OF FR-4 ANTENNA PARAMETERS

Parameters	CA (2.4 GHz)	Configuration-II (2.44 GHz)	Change
Bandwidth	55.6MHz	62.9MHz	+13.12%
Directivity	7.066 dBi	7.149 dBi	+1.174%
Efficiency	2.935 dB	3.636 dB	+23.88%
Gain	6.131 dBi	6.745 dBi	+10.01%
Power	6.861dBW/m^2	7.463 dBW/m^2	+8.774%
Ref. Coefficient	-18.84dB	-45.25 dB	+140.1%
Size	76X58mm^2	70X55mm^2	-14.49%

TABLE-V
COMPARISON OF ALL CONFIGURATIONS

Parameters	Conventional Antenna	Config.-I	Config.-II
Bandwidth	Narrow	Improved	Improved
Directivity	Low	Improved	Improved
Efficiency	Low	Improved	Improved
Gain	Low	Improved	Improved

TABLE-VI
COMPARISON WITH EXISTING PROTOTYPES

Parameters	[3]	[4]	Config.-1	Config.-II
Bandwidth	242 MHz	100 MHz	26.2 MHz	62.9 MHz
Directivity	6.730 dBi	6.976 dBi	7.989 dBi	7.149 dBi
Efficiency	2.985 dB	2.785 dB	3.065 dB	3.636 dB
Gain	5.8 dBi	5.93 dBi	7.145 dBi	6.745 dBi

Further, there is a need of extending their reach to various applications, parametric optimization is done by the Genetic Algorithm as electromagnetic optimizer is used as in Fig. 12 and Fig. 13 respectively. It directly involves with the success in saving electromagnetic resources with the yield of novel on approaches.

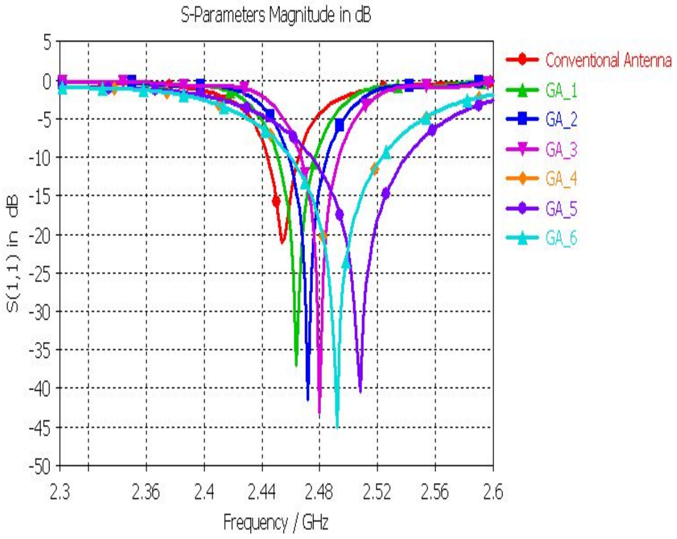


Fig.12 Variations in the parameters of EBG Structures as the behaviour has been observed on Metamaterial Antenna for the case of configuration-I as in Rogers RT Duroid 5870 substrate are used.

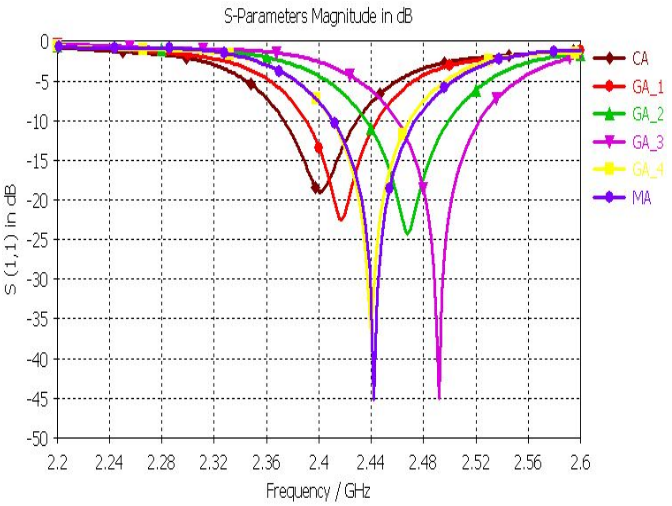


Fig.13 Variations in the parameters of EBG structures as the behaviour has been observed on Metamaterial Antenna for the case of configuration-II as in FR-4 substrate is used.

IV. CONCLUSION

In this article, the author want to grab the attention of the research community towards the fact that the performances of conventional antenna can be significantly improved to match with the expectations of modern applications. With the help of designed prototypes, illustrations were much clear & bright about prospectives of Metamaterials which acts as an agent to improve end-products. It's because in a current era of modern communications, the whole architecture system might not be changed. But end-products like antenna's can be upgraded to meet our requirements. Besides main concern which lie with the performances of conventional antenna where its ailments are solved, which was essentially required in case of specific applications.

APPENDIX

While implementing Genetic Algorithm, certain concepts [11] [12] needs to be taken care which are as follows:

1. Population
2. Parent
3. Child
4. Generation
5. Chromosome
6. Fitness

The author has chosen Genetic Algorithm over other most conventional techniques [12] because of following reasons:

1. It operates on group (or population) of trial solutions in parallel.
2. It normally operates on coding of function parameters (chromosome) rather than parameters themselves.
3. It use simple, stochastic operator (selection, crossover and mutation) to explore out the solution domain in search of an optimal solution.

For exploitation of Genetic Algorithms [11] [12], certain guidelines to be followed:

1. Population Size: 30-100 (Large populations provide more genetic diversity, enabling faster convergence as smaller population's yields out faster executions, especially when dealing on with a complicated fitness functions).
2. Probability of Crossover: 0.6-0.9 (Crossover is a way where GA optimizer searches for new and better most solutions. High crossover probability ensures a faster searching).
3. Probability of Mutation: 0.01-0.1 (It should be low as it introduces new genetic material into the search process, but also tends to push out the population's average fitness away from the optimal value).
4. Replacement Strategy: Steady State (It converges as faster than generational replacement in many applications. The lower values of replacement percentage as usually converges faster than higher values).

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