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Optimization of a Modified Rectangular Patch Antenna Array for X-band Applications

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Abstract

Objectives: To optimize the dimensions of Conventional Rectangular Patch Antenna using ant lion optimization and to design the 2 × 2 patch antenna array with the optimized modified rectangular patch antenna. **Methods/Statistical Analysis:** Analysis is done in the form of curve fitting equations and objective functions regarding the relations between performance and dimensional parameters of the patch antenna. In this work, length of the patch, width of matching line, height of the substrate and length of the ground plane are analyzed to achieve the desired performance characteristics of the patch antenna. Further, corporate feed method is used to design the different configurations of patch antenna array. **Findings**: An optimized rectangular patch antenna is designed by using ant lion optimization technique to achieve the required resonant frequency, S11 (dB), bandwidth and gain. Further, optimized design is transformed into modified rectangular patch, 1 × 2 array and 2 × 2 array to enhance the gain and required radiation pattern. The gain and bandwidth of the Modified Rectangular Patch Antenna array is 3.6 dBi and 718 MHz respectively, which shows improvement over the conventional design. Similarly 1 × 2 patch antenna array resonates at two frequencies which are 8.2 GHz and 9.6 GHz with a maximum gain of 8.1 dBi. The final design operates at 8 GHz (X-band) with a bandwidth of 1.65 GHz and a gain of 5.2 dBi. Also, the radiation pattern of the proposed 2 × 2 array consists of two major lobes adjacent to the null on broadside direction. **Application/Improvements:** The gain as well as bandwidth in the MRPA is improved by 20% and 10% respectively. The fractional bandwidth of the proposed 2 × 2 array is found to be 21.25%. The design covers spectrum of 8.025-8.40 GHz used for earth exploration satellite communication.

Keywords: Antenna Array, Ant Lion Optimization, Bandwidth, Gain

1. Introduction

In modern era, Microstrip Patch Antenna (MPA) is extensively used component in the commercial and military application due to its inherent advantages[1]. The 8.025-8.4 GHz band is used typically for the services of earth exploration satellite communication. These services are used frequently by military, space, commercial and other organizations. Further, the 8.1-8.2 GHz band is used specifically in meteorological satellite communication. In order to design a MPA for these services with desired performance, geometrical dimensions of the antenna are required to be optimized thus making it suitable for resonating at defined frequency in the given band or spectrum A number of conventional and non-conventional techniques are reported for the optimization of geometrical measurements of the MPA[2–6]. The design of a MPA for a particular application is viewed as a multi-objective problem for optimization.

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As only approximate solutions are possible for such problems, hence effective optimization techniques are required to be executed invariably to achieve best approximate solution for the design of MPAs. Different metaheuristic techniques have been reported till-date for this purpose under the category of non-conventional optimization methods for the optimal solution of such multi-objective problem. ALO, inspired by swarm intelligence, has been reported recently as one such promising algorithm. This algorithm, introduced originally by, mimics five major steps of hunting prey (Ant) in nature by Ant Lion including haphazard walk of ants, building of traps, allurement of ants in traps, grasping preys and re-construction of the traps. These five steps are executed in a systematic manner by the way of computational algorithm to solve given optimization problem. The algorithm has been applied successfully with convincing performance on a number of Benchmark Mathematical Functions including uni-modal, multi-modal and composite functions as well as real-time cantilever beam design problem[7]. Based on the grand success of this algorithm for the optimization of such problems, four different geometrical dimensions of the CRPA has been optimized in this article cumulatively to achieve desired performance. In order to do so, polynomial curve-fitting method is used to model the input-output parameters[8] of the proposed antenna. Based on the collative overall response of the CRPA in response to four geometrical dimensions, Ant Lion Optimizer is executed for achieving dimensional optimization of the CRPA with enhanced performance. Geometrical dimensions of the proposed MPA which are considered for optimization in the present work include patch length, dielectric height, quarter wave transformer width and length of partial ground plane. Accordingly, patch length is optimized for the purpose of tuning the CRPA suitably at desired resonating frequency. In addition to this, width of the matching quarter wave transformer is also optimized to achieve better return loss. Similarly, bandwidth of the design is optimized with the height of the substrate and impedance matching is optimized with dimensions of the ground plane.

2. Design of the Proposed Antenna Array

The design of the proposed Antenna is developed using a substrate of thickness 1.58 mm with dielectric constant 4.4. A Microstrip feed of 50 Ω is used with a λ/4 feed line to achieve suitable matching with the patch antenna. At first, simulation of a CRPA is supported in HFSS environment. Then optimization of CRPA is achieved with respect to its four geometrical parameters using ALO. Then optimized Conventional Rectangular Patch Antenna is further modified as well as optimized to get the same tuned at a given frequency for X-band satellite communication. Ultimately, by making the use of proposed optimized antenna elements, 1 × 2 element as well as 2 × 2 element arrangements of the patch antenna array is developed with enhanced performance. These design steps are detailed explicitly in the following section:

2.1 Simulation of CRPA

Various dimensions of the CRPA structure are computed using the conventional mathematical equations given in[1].

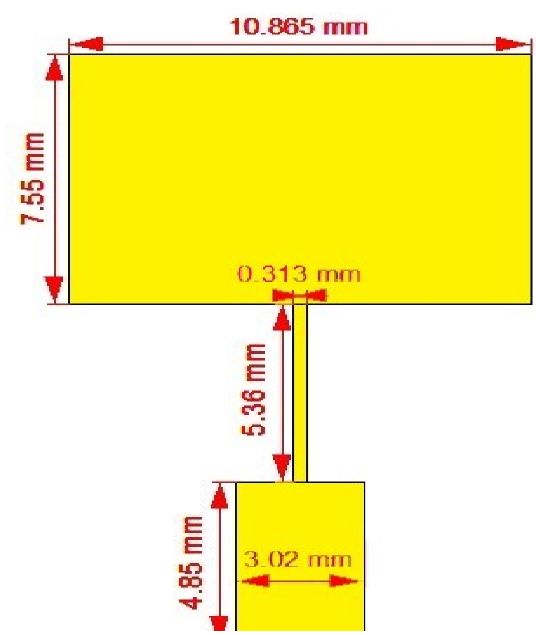

Figure 1. Conventional Rectangular Patch Antenna (CRPA).

The performance of the synthesized conventional patch antenna is examined for its compatibility with satellite communication in X-band. The geometrical design parameters of CRPA are shown in Figure 1.

2.2 Optimization of Conventional Rectangular Patch Antenna

Curve fitting method is used in MATLAB environment to establish mathematical relation between various dimensional limits of the antenna and performance parameters, e.g. length, width of matching line and thickness of substrate decides the resonating frequency, S_{11} (dB) and bandwidth respectively.

All the equations have been implemented in the next section by taking the set of values from the simulation results in the HFSS software. Each mathematical relation, leads to its corresponding objective function. By combining different objective functions, overall fitness function is deduced. By using the overall fitness obtained as a result of cumulative response of the CRPA, ALO is executed for achieving optimized rectangular patch. In its execution, an Ant Lion builds a sharp edged cone structure under the soil and waits for the prey. When the respective prey (Ant) slips into the hole, the prey tries to come out of the hole and Ant Lion throws sand on to the prey. This process is repeated until the respective prey gets exhausted in its action. Ultimately, Ant Lion consumes the body of the exhausted prey. After that Ant Lion builds another hole and the process repeats again and again [9-10]. It is supposed that fitness of the Ant should be more than the fitness of the corresponding Ant Lion, then and only then Ant Lion consumes body of the ant. An Ant Lion update its position to catch other ant. This process is imitated using the Equation (1) proposed in the work at[7]:

$$Antlion_k^i = Ant_k^i$$

If

Fitness (Ant_k^i) >fitness ($Antlion_k^i$)

(1)

Table 1. Input parameters of Ant Lion Optimizer

Detail of Parameters	Values
Number of Search Agents	100
Lower Bound for L	5 mm
Upper Bound for L	9 mm
Lower Bound for Wq	0.1 mm
Upper Bound for Wq	1 mm
Lower Bound for height of substrate	1 mm
Lower Bound for height of substrate	2 mm
Dimensions (number of variables)	3
Max Iterations	100

Where, $Antlion^{i}_{k}$ is the position of k-th antlion in i-th iteration and Ant^{i}_{k} shows the position of k-th ant at i-th iteration. In all the iterations fittest antlion produced is called elite. Due to this elite, the movement of all the ants have been altered during each iteration. Therefore, every ant update their position according to the equation (2) reported in the work at[7]:

Ant = (Roulette wheel selection + random walk selection)/2 (2)

The algorithm finds the minimized fitness function to obtain the user defined frequency and best returns loss at the optimized dimensional parameters. The input parameters for applying the ant lion optimization are shown in Table 1.

2.3 Synthesis of Modified Rectangular Patch Antenna Array

CRPA suffers from the low gain and bandwidth problems. To overcome these issues, Modified Rectangular Patch

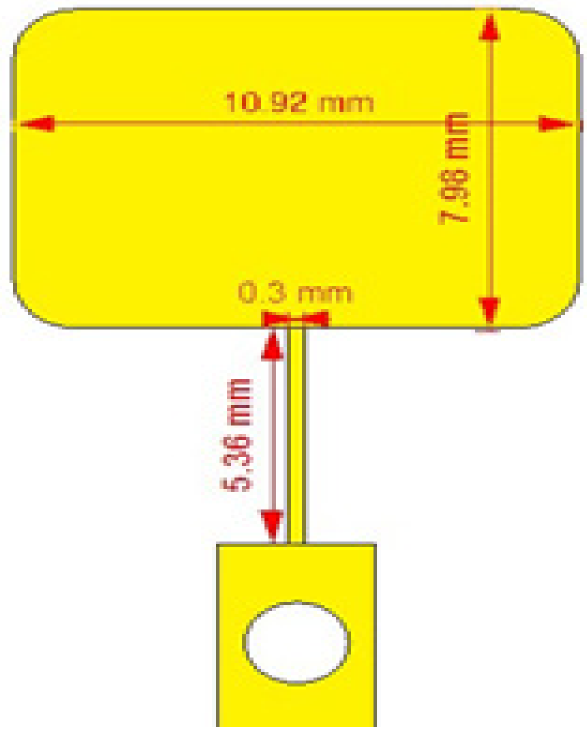

Figure 2. Modified Rectangular Patch Antenna (MRPA).

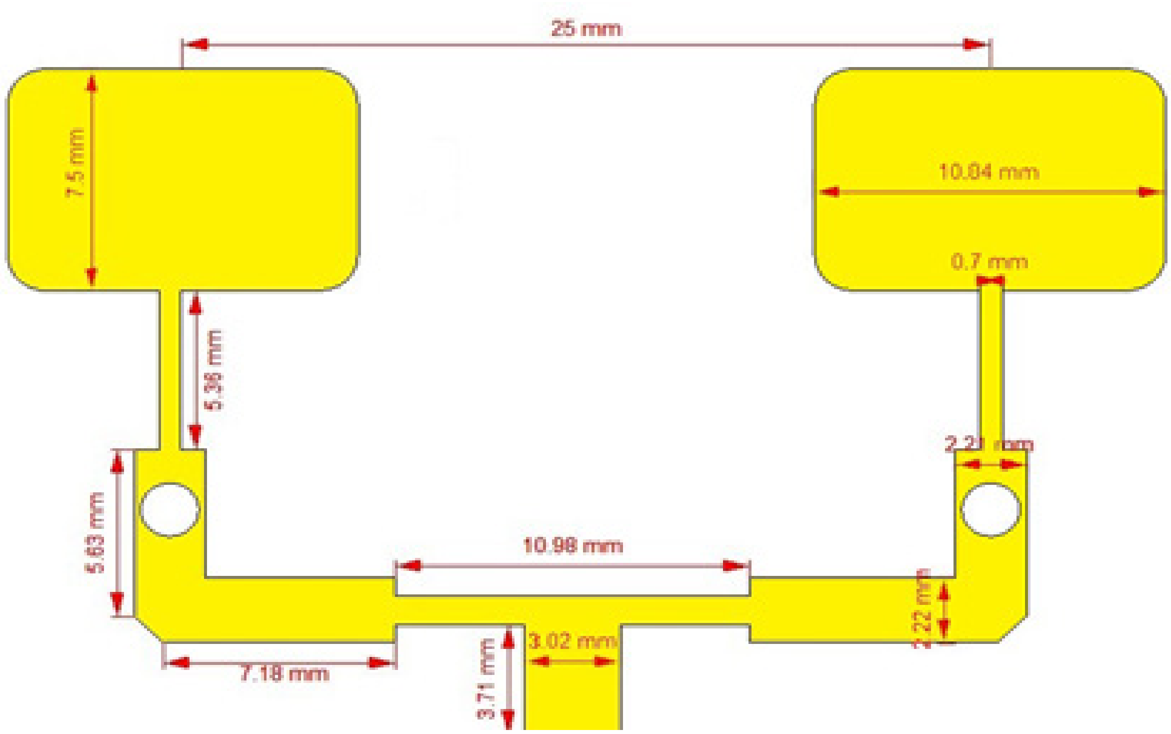

Figure 3. 1×2 element Modified Rectangular Patch Antenna.

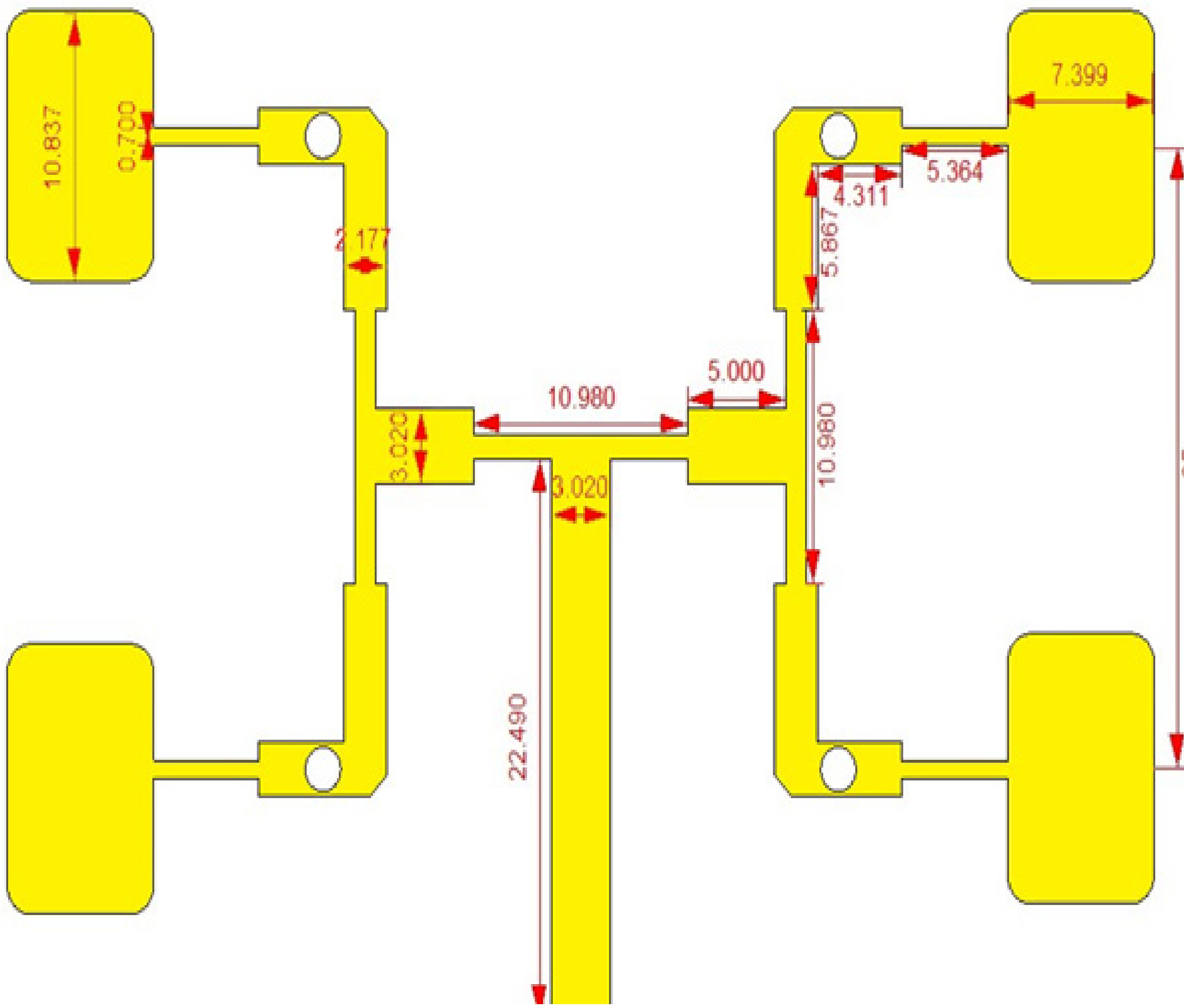

Figure 4. 2 × 2 Element Modified Rectangular Patch Antenna (All dimensions are in mm).

Antenna is presented. In which, the corners are rounded and a circular slot is cut in the feed to enhance gain and bandwidth as shown in Figure 2. Further improvement of parameters are achieved by the designing the 1 x 2 (MRPAA) as shown in Figure 3. In this design Radiation pattern of the broadside direction has been achieved. To get the null effect in the radiation pattern and two major lobes 2 x 2 Modified Rectangular Patch Antenna array has been designed as shown in Figure 4, which provides the wideband characteristics and high gain at desired frequency.

3. Results and Discussions

3.1 Performance Analysis of CRPA

3.1.1 Effect of Length of Patch

Operating frequency varies inversely with the length of antenna. So, length of the antenna as calculated is 7.86 mm and the resonance of 8 GHz is achieved. To get the required band of operation, length of the patch is opti-

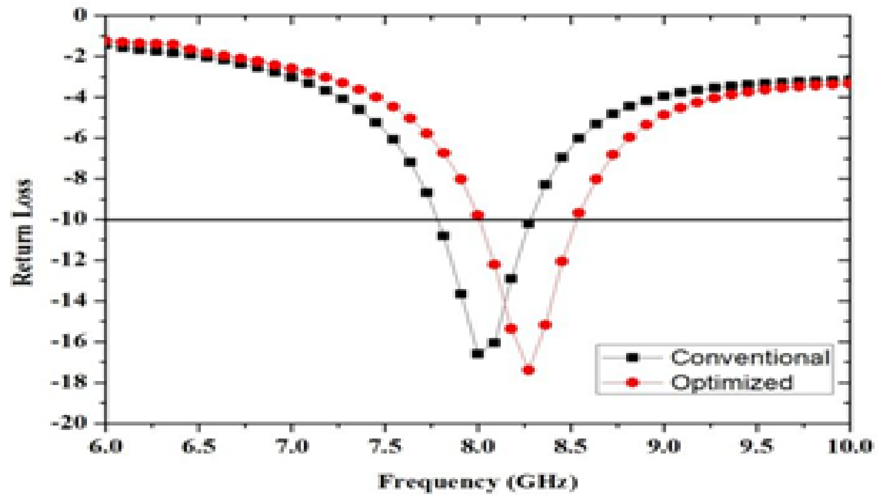

Figure 5. Effect of patch length on resonant characteristics of CRPA.

mized using ALO in combination with polynomial curve fitting interpolation. Equation (3) has been established using polynomial curve fitting method.

$$F = 0.0556 \times L^3 - 1.363 \times L^2 + 10.23 \times L - 15.17 \quad (3)$$

Above equation is applied in the ALO with the following fitness function to approximate the optimized length of the patch. Figure 5 shows the resonating frequency v/s S_{11} (dB) curve.

$$\text{Fitnees Function} = (8.3 - F)^2 \quad (4)$$

3.1.2 Effect of Width of Matching Line

At the calculated width of matching line which is 0.7 mm, the S_{11} (dB) is found to be -16 dB. Equation (5) shows relation between the width and the return loss with the polynomial curve fitting interpolation.

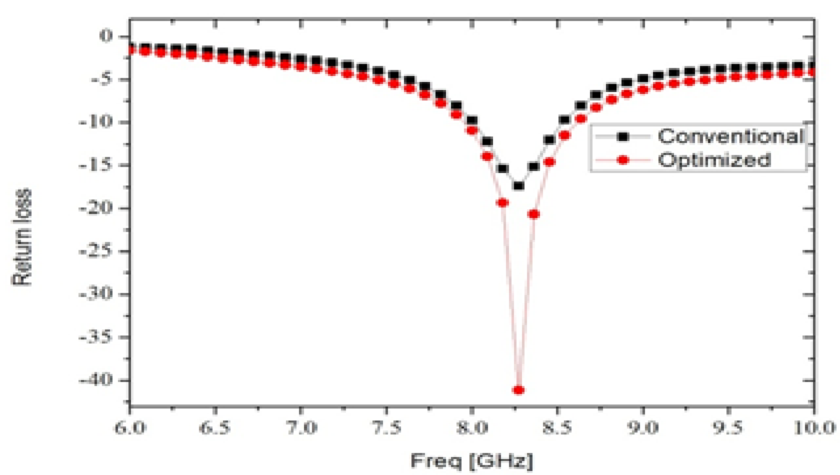

Figure 6. Effect of quarter wave transformer width on resonant characteristics of CRPA.

$$\text{Return Loss} = 58534 \times W_q^7 - 236010 \times W_q^6 + 387530 \times W_q^5 - 331920 \times W_q^4 + 157260 \times W_q^3 - 40027 \times W_q^2 + 4844.8 \times W_q - 228 \quad (5)$$

From above equation, following fitness function is minimized using ALO.

$$\text{Fitnees Function} = (37 + \text{Return Loss})^2 \quad (6)$$

Figure 6 shows the improvement in S_{11} (dB). The optimized width of the matching line is found to be 0.3 mm and corresponding return loss found is -41 dB.

3.1.3 Effect of Substrate Height

Narrow bandwidth is the major limitation of the MPAs. Bandwidth can be improved by increasing the thickness of substrate and the corresponding relation is shown in Equation (7).

$$\text{Bandwdith} = -13.021 \times h^4 + 571.64 \times h^3 - 1818.4 \times h^2 + 2480.4 \times h - 900.67^1 \quad (7)$$

Based on the above equation, the fitness function given in equation (8) is optimized with the help of ALO.

$$\text{Fitnees Function} = (662 - \text{Bandwdith})^2 \quad (8)$$

3.1.4 Effect of Partial Ground

In this section, dimensions of the ground plane also effect the characteristics of CRPA[11,12]. The various performance parameters are calculated at different lengths of the ground plane as shown in Table 2. Excellent impedance matching can be seen at certain dimension of the ground plane. The variations with ground plane are indicated in Figure 7.

From above table, it is seen that there is no direct synchronization of any performance parameter with the length of the ground plane.

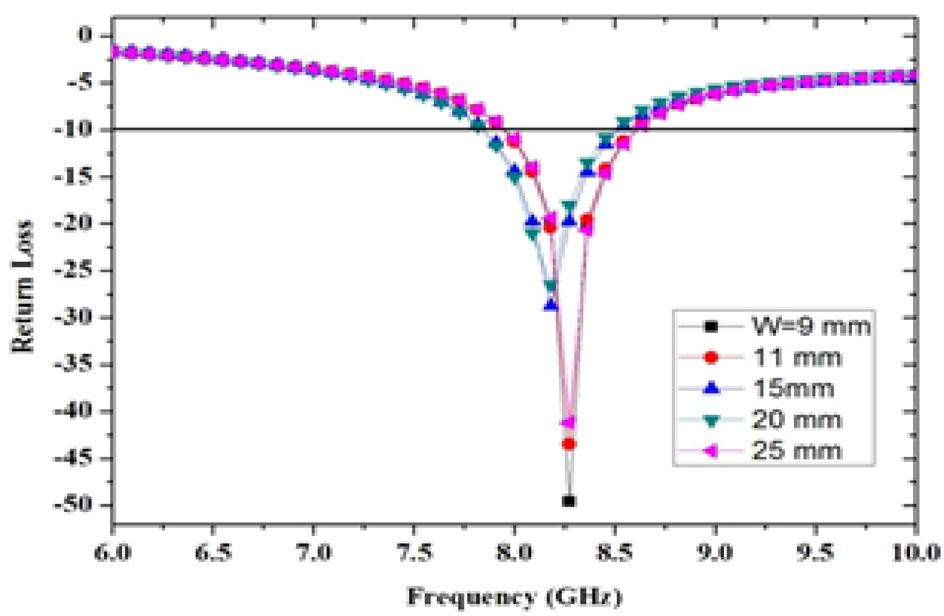

Figure 7. Effect of ground plane length on resonance characteristics of CRPA.

Table 2. Performance parameters of CRPA with different lengths of ground plane

Ground Plane Length (mm)	Return Loss (dB)	Resonant frequency (GHz)	Bandwidth (MHz)	Gain (dB)
9	-49.5814	8.2727	550	3.09
11	-43.4845	8.2727	661	3.15
15	-28.7432	8.18	680	3.04
20	-26.5117	8.18	649	3.05
25	-41.18	8.2727	661	3.07

3.1.5 Cumulative Response of the Optimized CRPA

The dimension calculation of RMPA is L = 7.86 mm, the resonant frequency is 8 GHz. To optimize the length for the required operating band, anti-lion optimization is used. The optimized length of the patch is L = 7.55 mm. The calculation width of the quarter wave transformer (W) is 0.7 mm and the S_{11} is -16 dB. The S_{11} is improved up to -40 dB after applying optimization on the width, the value of which is found to be 0.3 mm. The final resonant characteristics are shown in Figure 8. The radiation pattern of the optimized design is shown in the Figure 9 which shows the gain of 3.07 dBi at theta = 20° and phi = 270°.

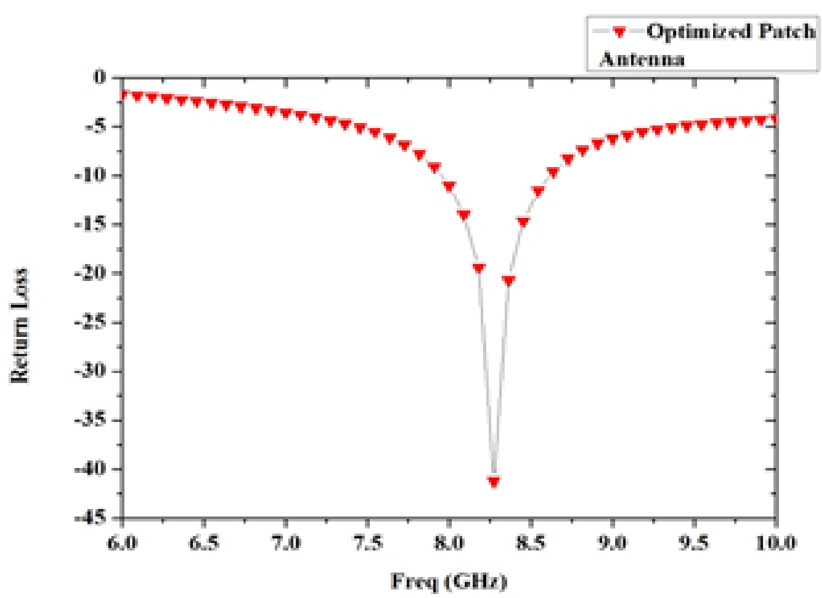

Figure 8. Return loss of optimized CRPA.

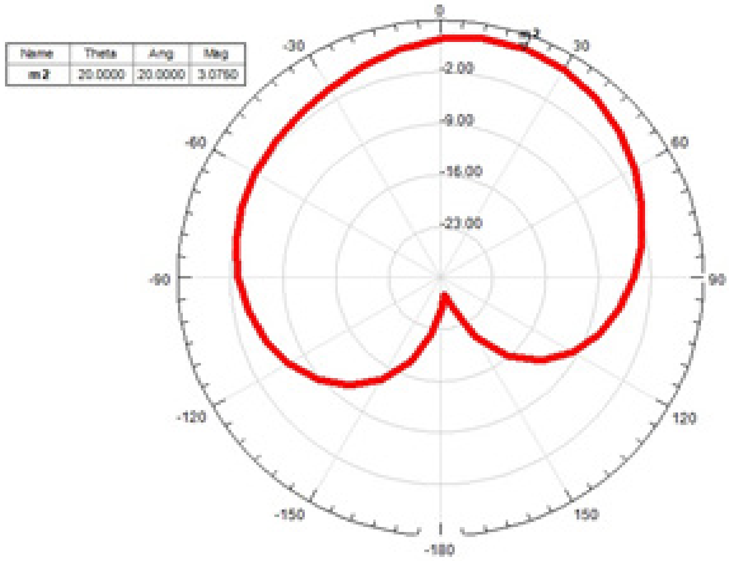

Figure 9. Radiation pattern of optimized CRPA.

3.2 Performance Analysis of MRPA

The return loss, VSWR and radiation pattern of the MRPA are shown in the Figure 10, 11 and 12 respectively.

The S_{11} of the MRPA is -32dB at 8.4 GHz and the VSWR is less than 2. Also the gain has been improved to be 3.6 dB at 8.4 GHz as shown in Figure 13, which was otherwise of 3 dBi in case of CRPA.

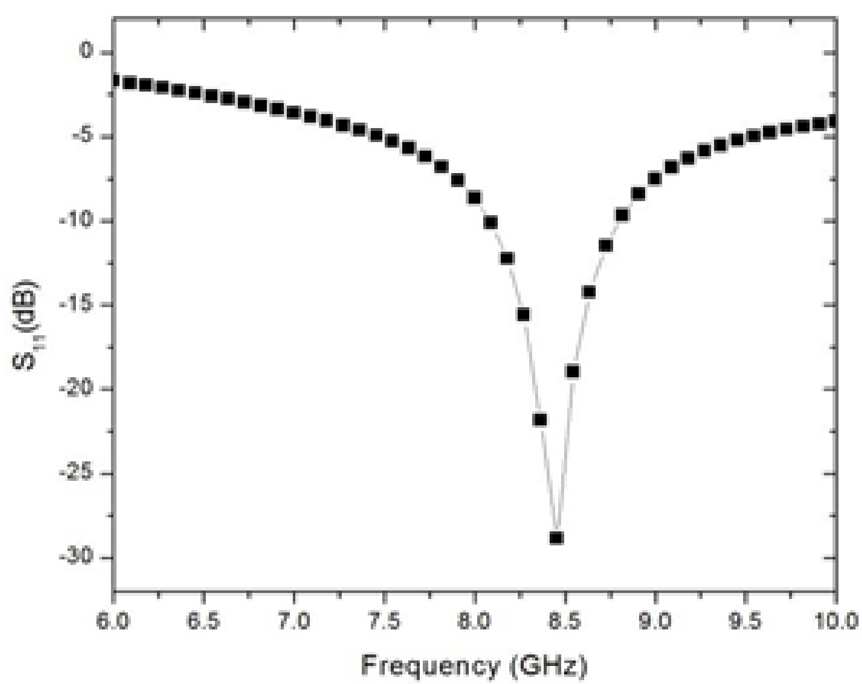

Figure 10. Return loss of MRPA.

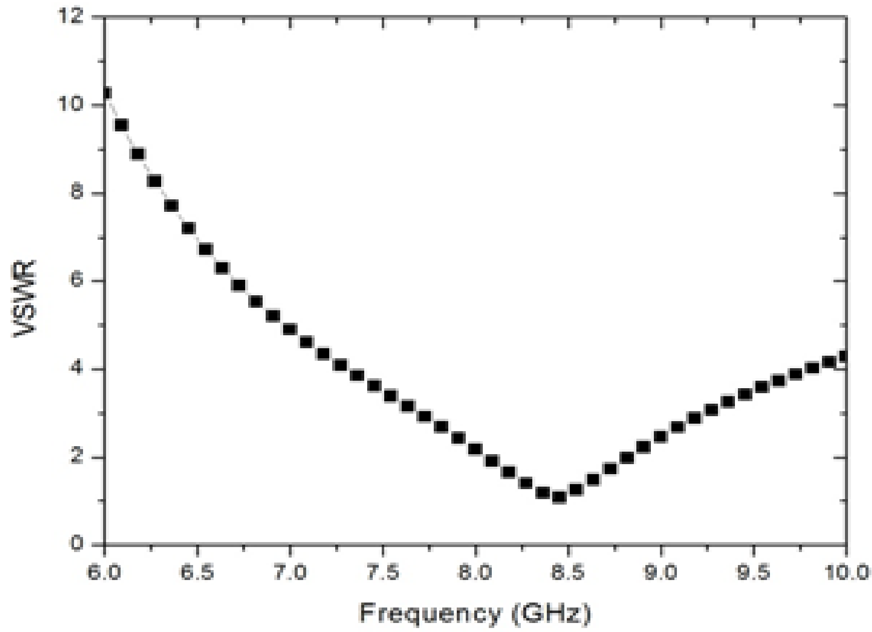

Figure 11. VSWR of MRPA.

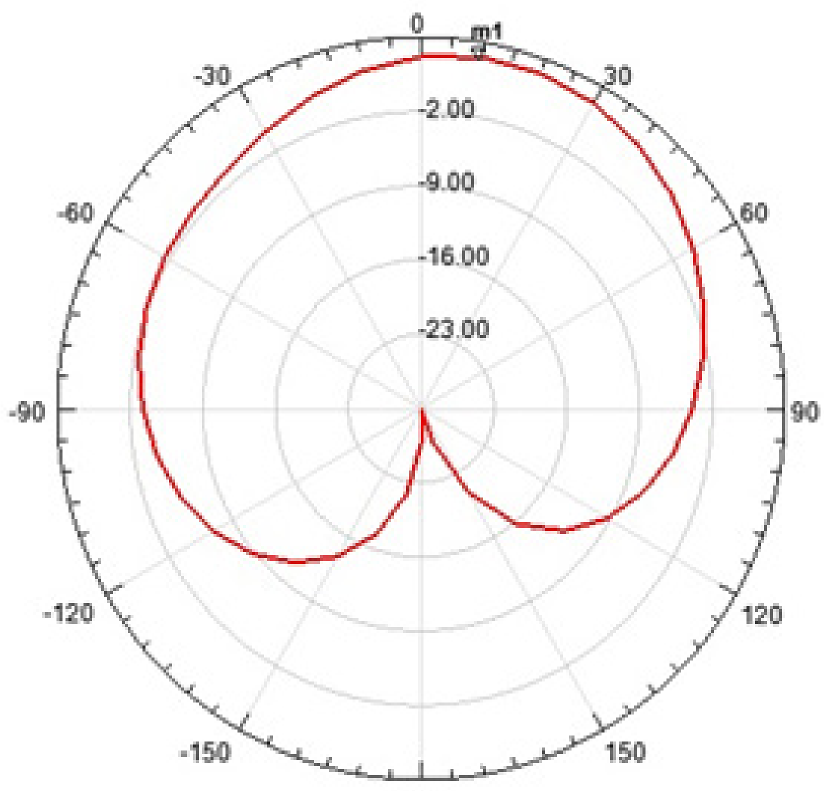

Figure 12. Radiation pattern of MRPA.

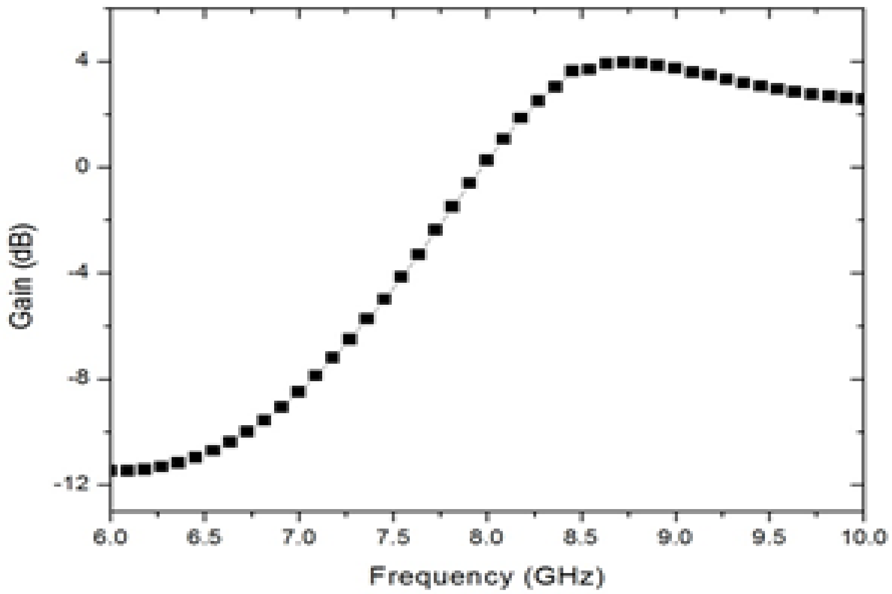

Figure 13. Gain vs. frequency graph of MRPA.

3.3 Performance Analysis of 1 × 2 Element MRPAA

The S_{11} (dB) and VSWR of the 1 × 2 MRPAA are shown in Figure 14 and 15 respectively. The proposed antenna array operates at dual frequencies, i.e., 8.2 and 9.6 GHz with a return loss of -18 and -13.8 dB respectively. Also, VSWR at these two resonating frequencies is found to be 1.29 and 1.51 respectively.

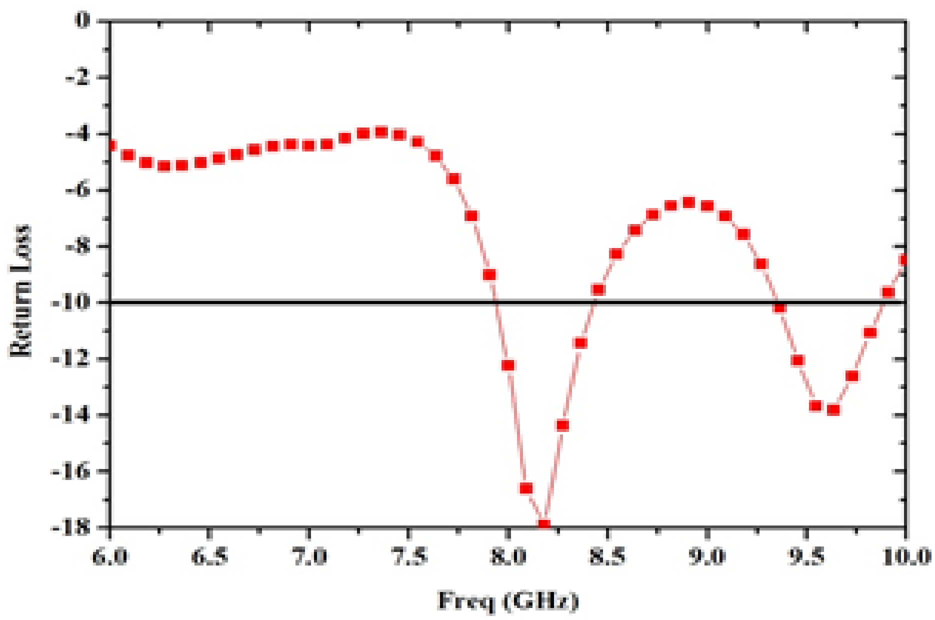

Figure 14. Return loss of 1 × 2 element MRPA.

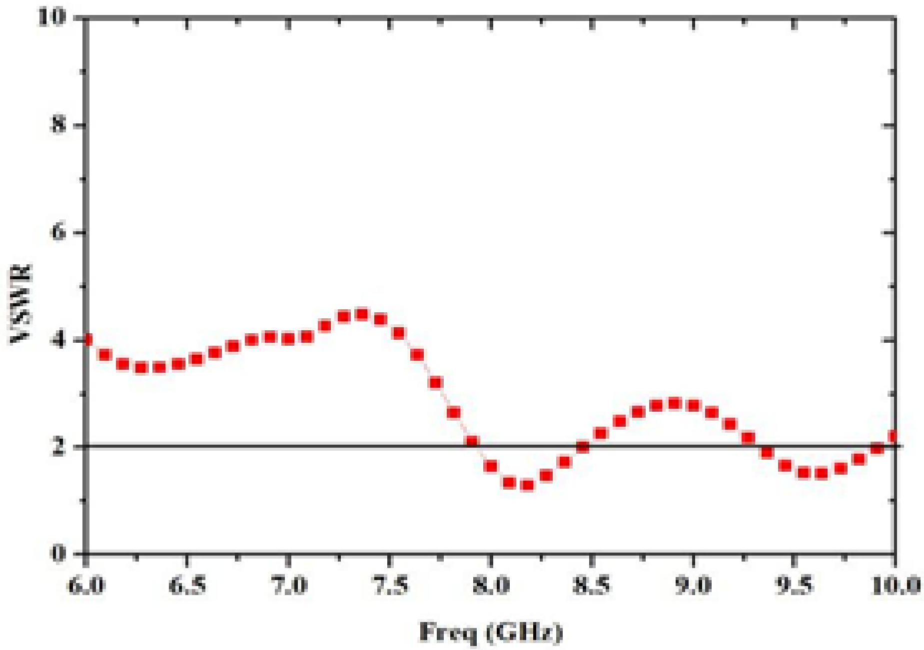

Figure 15. VSWR of 1 × 2 element MRPA.

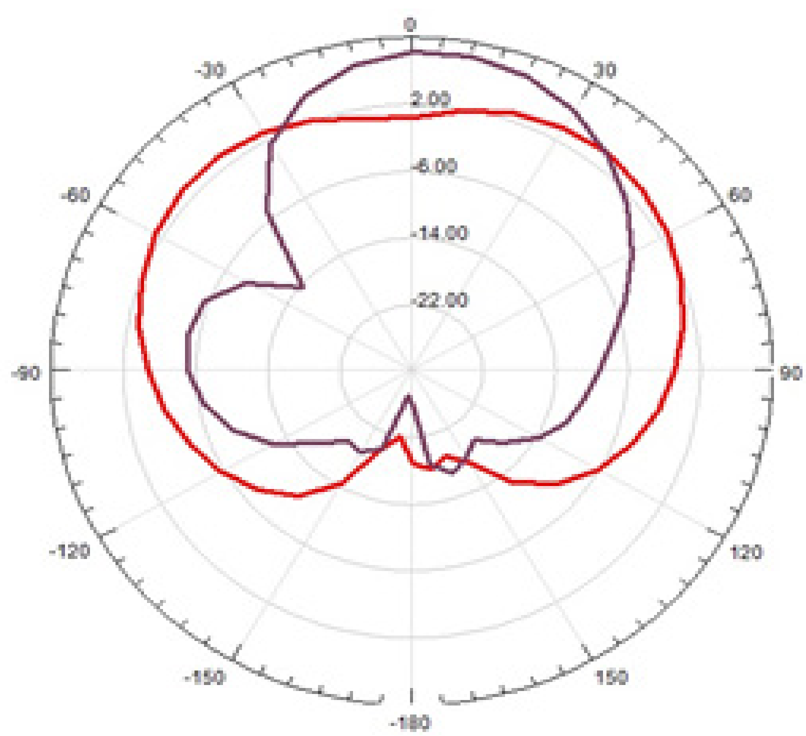

Figure 16. Gain radiation pattern of 1 × 2 element MRPAA.

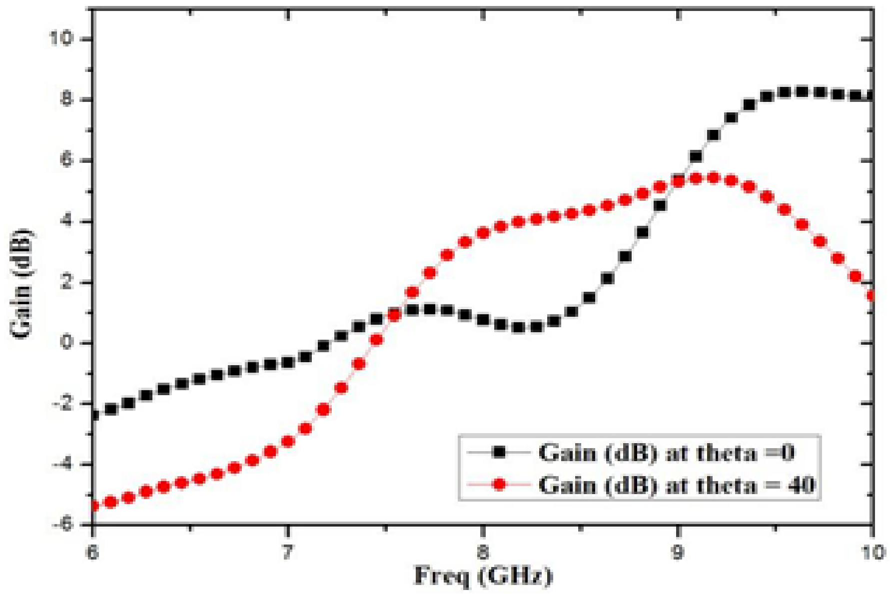

Figure 17. Gain vs. frequency curve of 1 x 2 MRPA.

The Gain Radiation Pattern of 1 × 2 Modified Rectangular Patch Antenna array at both the resonating frequencies is shown in Figure 16. It is observed that the gain at 8.2 GHz is about 4 dB and gain at 9.6 GHz is 8.1 dBi with theta = 40° and 0° respectively and phi = 270° as shown in Figure 17.

3.4 Performance Analysis of 2 × 2 Elements MRPAA

Fabricated final proposed design is shown in Figure 18. The S_{11} (dB) and VSWR of the 2 × 2 MRPAA are shown in the Figures 19 and 20 respectively. From the figures,

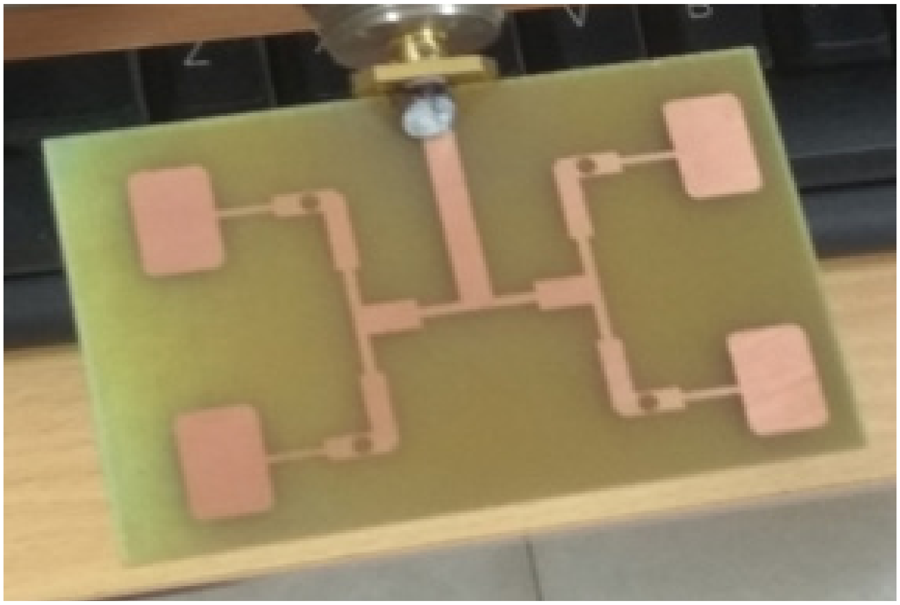

Figure 18. Fabricated prototype.

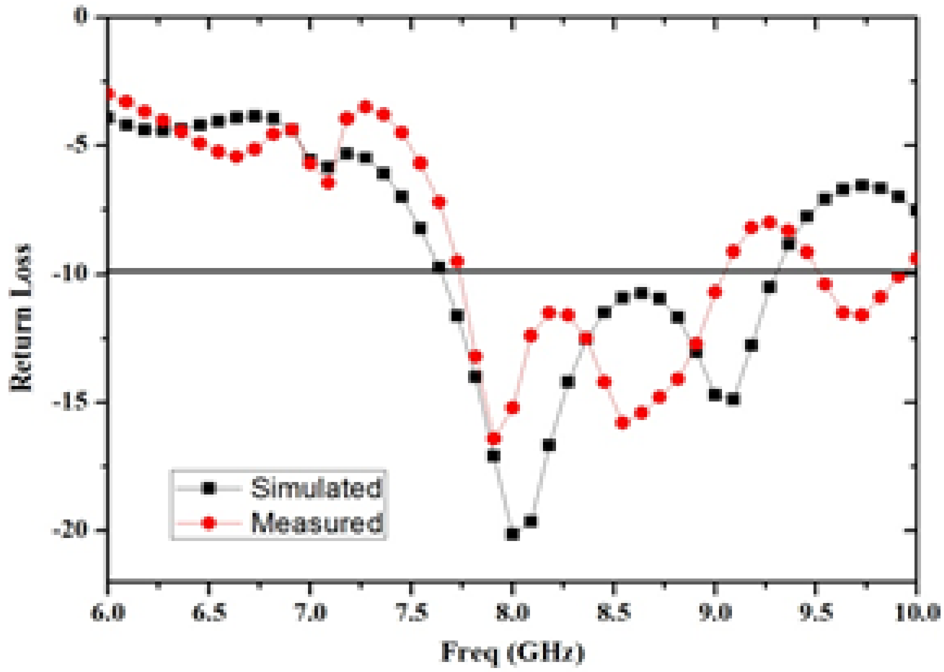

Figure 19. Measured return loss of 2 × 2 element MRPAA.

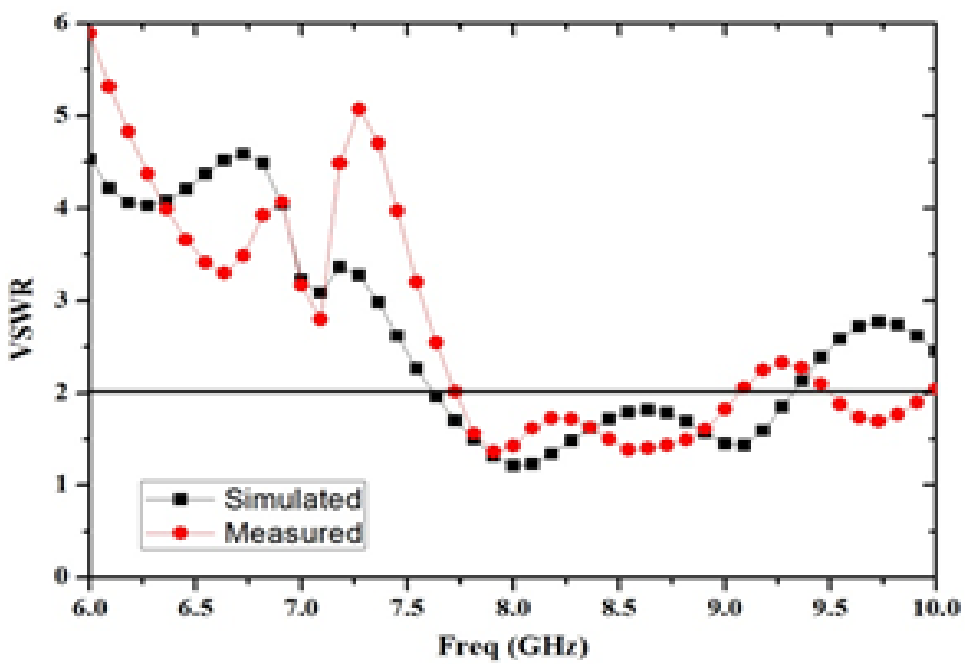

Figure 20. VSWR of 2 × 2 element MRPAA.

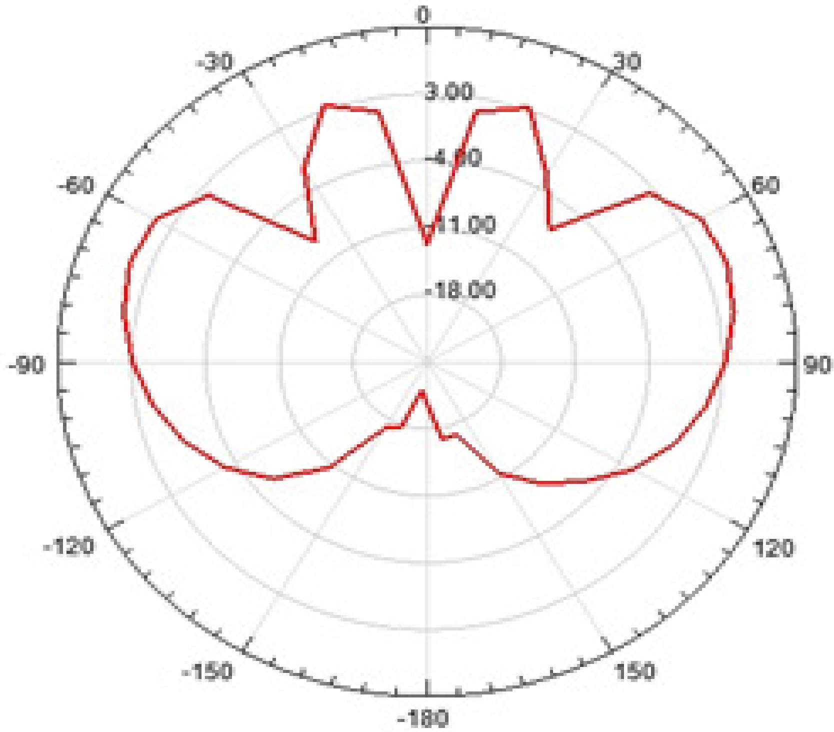

Figure 21. Radiation pattern of 2 × 2 element MRPAA.

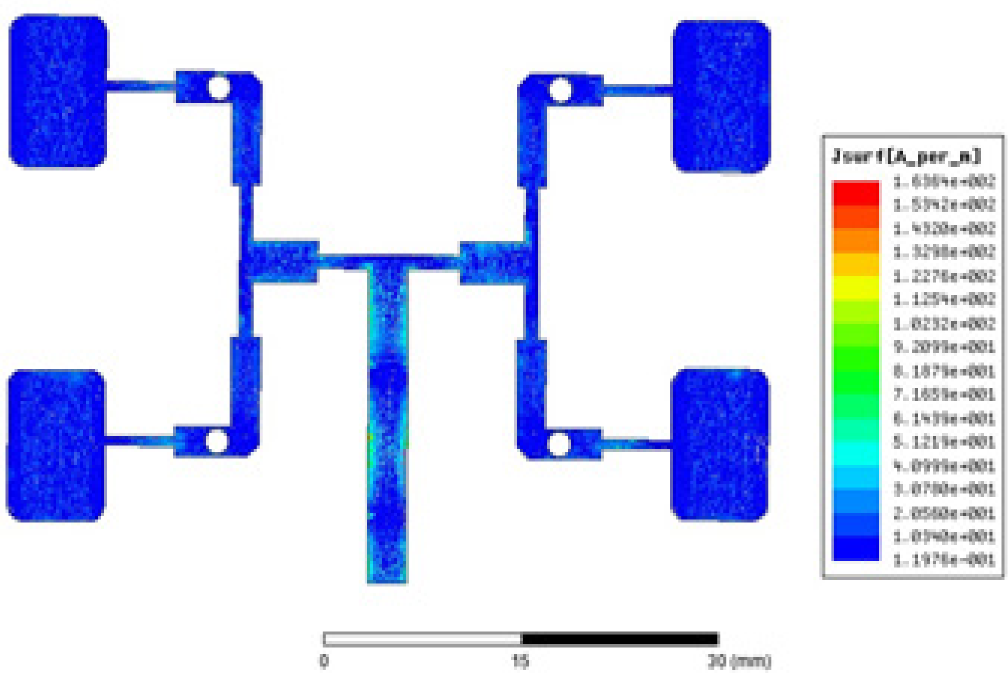

Figure 22. Current distribution of 2 x 2 MRPA.

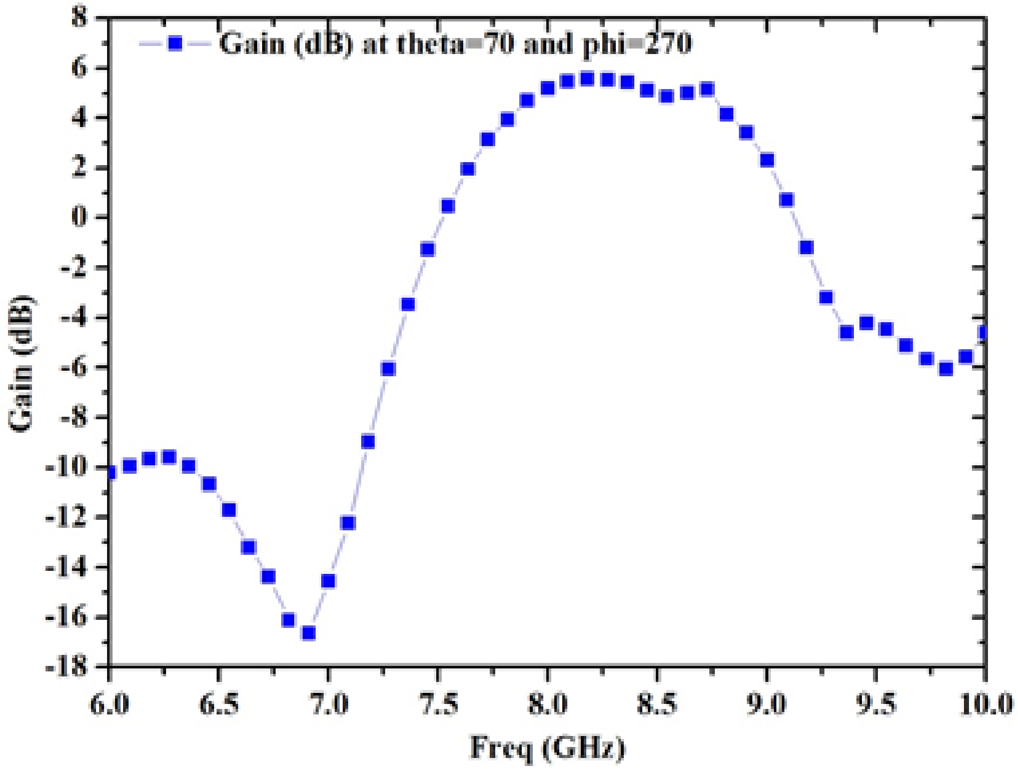

Figure 23. Gain vs. frequency curve of 2 x 2 MRPA.

it is found that return loss at resonating frequency of 8 GHz is -20.1 dB and VSWR is 1.21. It is also seen that the proposed 2 × 2 patch antenna array shows wideband characteristics. The comparative results of measured and

Table 3. Performance parameters of CRPA, MRPA, 1 × 2 element MRPAA and 2 × 2 element MRPAA

Parameters	CRPA	MRPA	1 × 2 Element MRPAA		2 × 2 Element MRPAA
Resonant Frequency (GHz)	8.3	8.4	8.2	9.6	8
Return Loss (dB)	-41	-32	-14.2	-14	-20.1
Gain (dBi)	3.07	3.6	4	8.1	5.2
Bandwidth	662 MHz	718 MHz	377 MHz	485 MHz	1.65 GHz
VSWR	1.01	1.07	1.48	1.49	1.21

simulated have been shown in Figure 19. Which shows a close concurrence with each other? The radiation pattern, current distribution and gain variations are shown in Figure 21, 22 and 23. The radiation pattern of the design shows two major lobes and a null position in broadside direction. Also, there is a uniform current distribution in the proposed deign.

3.5 Final Results

It is observed from Table 3 that MRPA has improved performance Parameters over the CRPA in terms of gain and bandwidth by 20% and 10% respectively. Similarly the 1 × 2 MRPAA shows dual band characteristics in X-band with improved gain and 2 × 2 MRPAA covers wideband with improved gain as compared to 1 × 2 Array.

4. Summary and Conclusion

The results of this article show that the CRPA resonates at 8.3 GHz and covers a spectrum of 8.025-8.40 GHz used for earth exploration satellite communication. Further, the gain is found to be 3.07 dB with a S_{11} of -41dB. The gain as well as bandwidth in the MRPA is improved by 20% and 10% respectively. Similarly, in 1 × 2 array, dual-band characteristics have been achieved with an extremely high gain of 8 dB. Ultimately, 2 × 2 Modified Rectangular Patch Antenna Array has been designed to achieve wideband characteristics. The fractional bandwidth of the proposed 2 × 2 array is found to be 21.25%. Also, the radiation pattern of the proposed 2 × 2 array consists of two major lobes adjacent to the null on broadside direction. The above feature makes the proposed design suitable for radar systems, where jamming of the signal is required invariably. Ant Lion Optimizer, inspired by swarm intelligence, is an effective optimization technique for the design of MPA because it ensures consistency in its performance. Moreover, the technique is found to be simpler as compared to other contemporary algorithms because fewer parameters are required to be adjustment for its execution. The work is under further progress for the design of multi-element Antenna Array using Modified Rectangular Patch Antenna proposed in the present work.

5. Acknowledgement

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