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Sequential Nonlinear Programming based Optimization for Z-Shape Microstrip Antenna Design

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Abstract : The patch antenna is one of the important elements in modern wireless communication systems and hence its design optimization is an important aspect for improving the overall performance of the system. In this paper, sequential nonlinear programming optimization technique has been utilized in HFSS software for optimization of the Z-shape patch antenna dimensions in order to achieve return loss, VSWR, directivity and gain. The designed antenna is to operate in Wi-Max / S- band and C- band satellite application with the centre frequency at 3.4 GHz, 4.25 GHz, 4.7 GHz and various important performance metrics of the patch antenna are analysed for performing comparative analysis between un-optimized patch antenna and optimized patch design. The main point of the paper is to examine the suitability of sequential nonlinear programming for antenna parameter optimization to achieve the design objectives subject to constraints. The basic principle of sequential approximations is to replace the given nonlinear problem by a sequence of quadratic sub problems that are easier to solve.
Keywords: Microstrip antenna, Wi-Max, multi band antenna, dual band antenna, broadband antenna, optimization

1. INTRODUCTION

The patch antennas are popular for their attractive features like: low profile, ease of fabrication, light weight and compatibility with Monolithic Microwave Integrated Circuits (MMICS). The patch antennas are used in satellite communication, wireless and microwave applications due to their compact and planar structures [1-3]. The main disadvantage is an intrinsic limitation in band width due to the resonant nature of the structure of the patch. The intensive research has been done to develop bandwidth enhancement techniques for patch antenna [4-6]. The popular methods for enhancement of band width are increasing height of substrate and adding parasitic elements to the patch. In order to overcome the shortcomings of the patch antenna it is important to make an optimal design of antenna for best performance. In this case various existing optimization algorithms can come handy. Sequential nonlinear programming algorithm is one of the global optimization algorithms has been used widely in the past by antenna designers [7], [8] for the optimization of the patch shape and size in order to achieve better overall performance of the antenna.

In this paper, the patch antenna and Z-shape patch antenna are designed using HFSS. The inbuilt optimization software in HFSS are sufficient for optimization of the designed parameters of the antenna [9] in order to get objective functions like S- parameter, VSWR, bandwidth, directivity, gain etc of designed antenna. Here, sequential nonlinear programming algorithm has been used for the optimization of Z- shape patch antenna dimensions operated at 3.4 GHz, 4.25 GHz and 4.7 GHz for Wi-Max / S- band

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& C- band satellite application. It was exactly used to optimize the slit width (L6). It has been verified that by cutting the slots into radiating edges of microstrip patch antenna, a triple band frequency response is achieved. The performance is improved by inserting a pair of slits in an appropriate radiating edge to form Z-shape patch antenna. In this work, a geometric Z-shape is developed from a rectangular patch, and then optimization is done in order to achieve better overall performance of the antenna.

The antenna is designed using FR4- epoxy substrate with a dielectric constant (ε_r) of 4.4 and a thickness of 1.6 mm respectively. The simulated result shows that the performance of the optimized Z-shape patch antenna using sequential nonlinear algorithm is better than the un- optimized in terms of the return loss and VSWR. To increase the bandwidth of antennas, including increase of the substrate thickness, the use of low dielectric substrate, the use of various impedance matching and feeding techniques, the use of multiple resonators and the use of slot antenna geometry, there are numerous and well known methods [10].

While optimizing the antenna parameter, the overlapping problems most often encountered using HFSS. The best possible optimization is done with the calibration and redesigning of the antenna in HFSS simulation tool.

To achieve optimal gain, pattern performance, bandwidth, VSWR and so on subject to specified constraints, antenna design is a topic of great importance to electromagnetic and involves the selection of antenna physical parameters. In finding the optimum solution or unconstrained maxima or minima of continuous and differentiable functions, the classical optimization techniques are useful. These are analytical methods and make use of differential calculus in locating the optimum solution. The sequential nonlinear programming studies the general case in which the objective function or both contain nonlinear parts. The work has been performed by interfacing the sequential nonlinear programming algorithm to An soft High Frequency System Simulator (HFSS). The paper is organized as follows: section II presents a design approach for Z- shape patch antenna, section III gives a brief about sequential nonlinear programming algorithm and the flow chart used, in section IV simulation results are presented and finally in section V conclusion is drawn.

2. ANTENNA DESIGN

A. Design Methodology

Microstrip patch antennas consist of a very thin metallic strip (patch) placed on a ground plane where the thickness of the metallic strip is restricted by $t << \lambda_0$ and the height is restricted by $0.0003\ \lambda_0 \le h \le \lambda_0$, where λ_0 is the free space wavelength. The microstrip patch is designed so that its radiation pattern maximum is normal to the patch. For a rectangular patch, the length L of the element is usually $\lambda_0/3 < L < \lambda_0/2$. The dimension has major impact on operating frequency [11-12].

B. Antenna Design Procedure

The bandwidth of an antenna is mainly determined by the thickness, the nature of the dielectric substrate and the geometry of the antenna. To expose the band width matter in simple planar structures and to give a benchmark in terms of space and bandwidth, a rectangular patch has first been sized. The dimensions of the antenna can be deduced from analytical expressions [1], [4].

(*a*) Width of Patch :

$$W = \frac{c}{2f_0}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

(*b*) Effective Dielectric Constant :

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-\frac{1}{2}}$$

(*c*) Due to fringing effects the change in dimension of length :

$$\Delta L = \frac{\left(\varepsilon_{reff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)}$$

(*d*) Length of Patch :

$$L = \frac{c}{2 f_0 \sqrt{\varepsilon_{reff}}} - 2\Delta L$$

Where, ε_r = dielectric constant,

h = Substrate thickness,

f_0 = Resonant frequency

Increasing the width of this antenna is one of factors controlling its bandwidth. Nevertheless, it is very difficult to obtain a satisfactory result with a simple shape microstrip patch antenna. That is why we propose Z-shape geometry in order to widen the bandwidth of the antenna while retaining reasonable dimensions. This geometry changes the distribution of surface current density generating multiple resonances.

Table 1

Optimized Dimensions of Proposed Antenna

Un- Optimized dimensions of patch antenna	
Parameter	*Value*
Substrate	FR4- epoxy
Centre frequency (f_r)	2.32 GHz, 3.62 GHz
Height of substrate (h)	1.6 mm
Loss tangent	0.02
Dielectric constant (ε_r)	4.4
Width of patch (W)	38.04 mm
Length of patch (L)	29.44 mm
Feed width (w_0)	1.8 mm
y_0	5 mm
x_0	0.6 mm
Un-optimized dimensions of Z-shape patch antenna	
Parameter	*Value*
L_1	30 mm
L_2	5 mm
L_6	6 mm
L_7	32 mm
Optimized dimensions of Z-shape patch antenna	
Parameter	*Value*
L_6	7.6153 mm

The goal of designing antenna at 3.4 GHz, 4.25 GHz and 4.7 GHz was to get better performance using optimization for Wi-Max / S- band & C-band Satellite application. The width of the rectangular patch antenna is usually chosen to be larger than the length of the patch to get higher bandwidth. To design patch antenna lower dielectric constant is used because in case of lower dielectric constant of the substrate, surface wave losses are more severe and dielectric and conductor losses are less severe. Table 1 shows the specifications for the proposed microstrip patch antenna.

C. Design of Z-shaped microstrip patch antenna

The most important design features of the patch are its width (W), length (L), width of transmission line and the length of the feeding line. The patch is fed by a 50 Ω inset feed. The geometry and configuration of Z-shaped microstrip patch antenna is shown in Fig. 1 and Fig. 2.

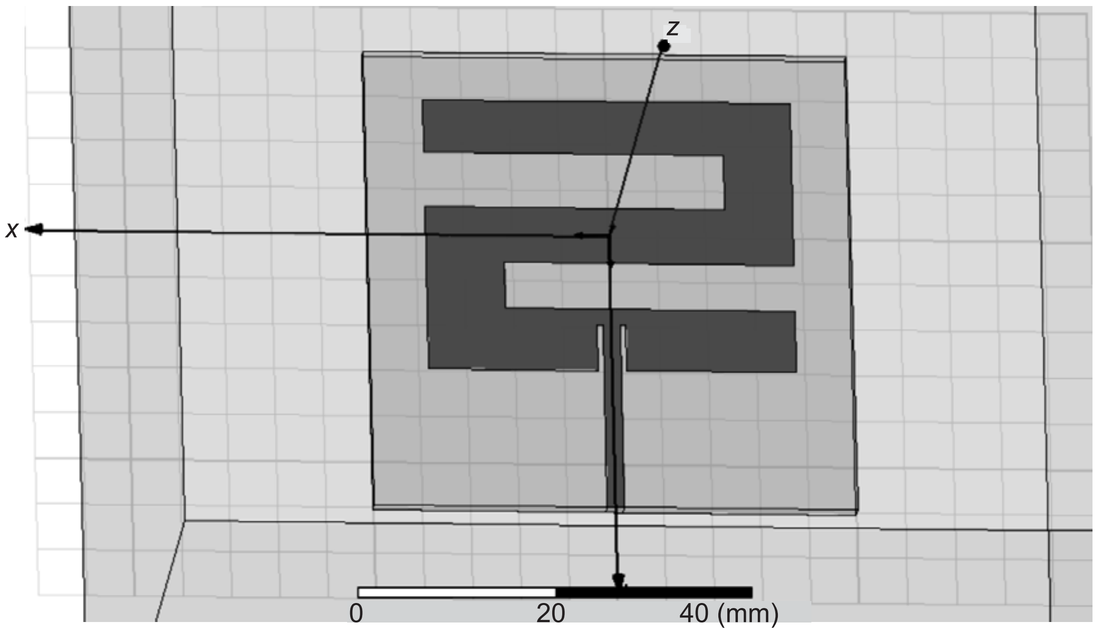

Figure 1: Un-optimized Z- shape microstrip patch antenna

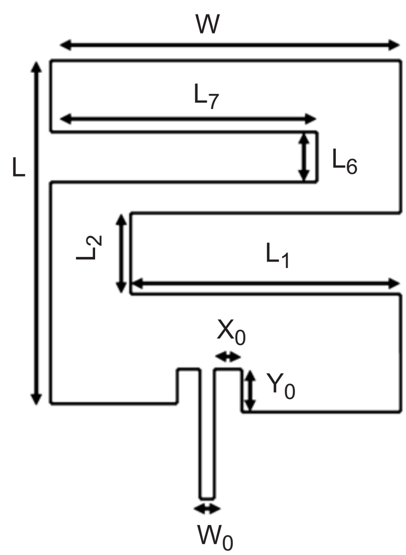

Figure 2: Patch configuration of Z- shape microstrip patch antenna

In patch antenna the feed line impedance (50 ohm) is always same as the resistance at the edge of the patch which is usually few hundred ohms depending on the patch dimensions and the substrate used. As a result the maximum power is not being transferred and input mismatch affects the antenna performance. The input impedance of the rectangular patch antenna decides the matching between feed line and patch.

According to the Transmission line theories, the resistance of the patch varies as a cosine squared function along the length of the patch.

The proposed antenna is the Z – shape patch antenna and after theoretical calculation for the rectangular microstrip patch antenna the optimization technique is used for the desired output. The parameters defined by HFSS are generally controlled by bound and direction with fixed rate. It has been observed that for any variations of the optimization parameters, overlapping problems arise in the HFSS simulation and the iterations terminate prematurely with an error. This error can be minimized by using the powerful optimization tool.

3. SEQUENTIAL NONLINEAR PROGRAMMING ALGORITHM

The basic principle of sequential approximations is to replace the given nonlinear problem by a sequence of quadratic sub problem that are easier to solve. Sequential Nonlinear Programming Algorithms consider the equality constrained problem:

$$\min\ f(x) \quad \text{subject to } h(x) = 0$$

Where, x represents the design variable set or vector. And $f(x)$ is the objective function. The other functions $h(x)$ are equally constraints. Using the Lagrange – Newton method described in most optimization books at the k^{th} iteration, we have

$$\begin{bmatrix} W_k & A_k^T \\ A_k & 0 \end{bmatrix} \begin{bmatrix} S_k \\ \lambda_{k+1} \end{bmatrix} = \begin{bmatrix} -\nabla f_k^T \\ -h_k \end{bmatrix} \tag{1}$$

Where

$$W = \nabla^2 f + 1\,\lambda^T \nabla^2 h,$$
$$A = \nabla h$$
$$\lambda = \text{vector of Lagrange multipliers.}$$

Solving the above equation iteratively, we can obtain the iterates $x_{k+1} = x_{k+sk}$ and λ_{k+1} which should eventually approach x and λ, the optimal values. Alternatively, we may observe that the above equation can be viewed as the Karush – Kuhn – Tucker (KKT) condition for the quadratic model.

$$\min \quad s_k q(s_k) = f_k + \nabla_x L_k s_k + \frac{1}{2} S_k^T W_k s_k$$

$$\text{subject to} \quad A_k s_k + h_k = 0 \tag{2}$$

$$\text{Where,} \quad \nabla_x L_k = \nabla f_k + \lambda^T{}_k \nabla h_k$$

Solving the quadratic programming sub problem (2) gives the same s_k and λ_{k+1} as solving equation (1) and thus two formulations are equivalent. In the second formulation, the values x and λ will be obtained from solving a sequence of quadratic programming (QP) sub problems, hence comes the name of SQP methods for the relevant algorithms. The QP sub problem can be solved efficiently by some general NLP algorithms such as reduced space or projection methods or augmented Lagrangian methods. Using active set strategy, we can also handle problems with both equality and inequlity constraints.

Fig. 3 shows the flow chart used to design Z- shape patch antenna. First we calculate the antenna parameters that we analyse its performance, if the results are not satisfied we use sequential nonlinear programming optimization. The optimization is terminated when criteria is met. After five iterations, the sequential nonlinear programming optimizer found the following optimal values for the parameters: L6 = 7.61 mm (Fig. 2 and Table 1).

4. SIMULATION RESULTS

The Z-shape patch antenna resonates at three bands of frequency at 3.35 GHz, 4.25 GHz and 4.6 GHz. These frequencies are related to the dimensions (L_1, L_2 and L_6, L_7). These dimensions are linked by the fact that the single excitation point must have matched impedance (50 Ω) with the two resonant frequencies.

Rectangular Patch antenna has been designed in HFSS software and various important performance metrics are measured to analyse the performance of the designed Z-shape patch antenna (Fig. 1). Now the Z-shape patch antenna has been optimized to get the best possible results in all the possible ways and final results are presented in this section.

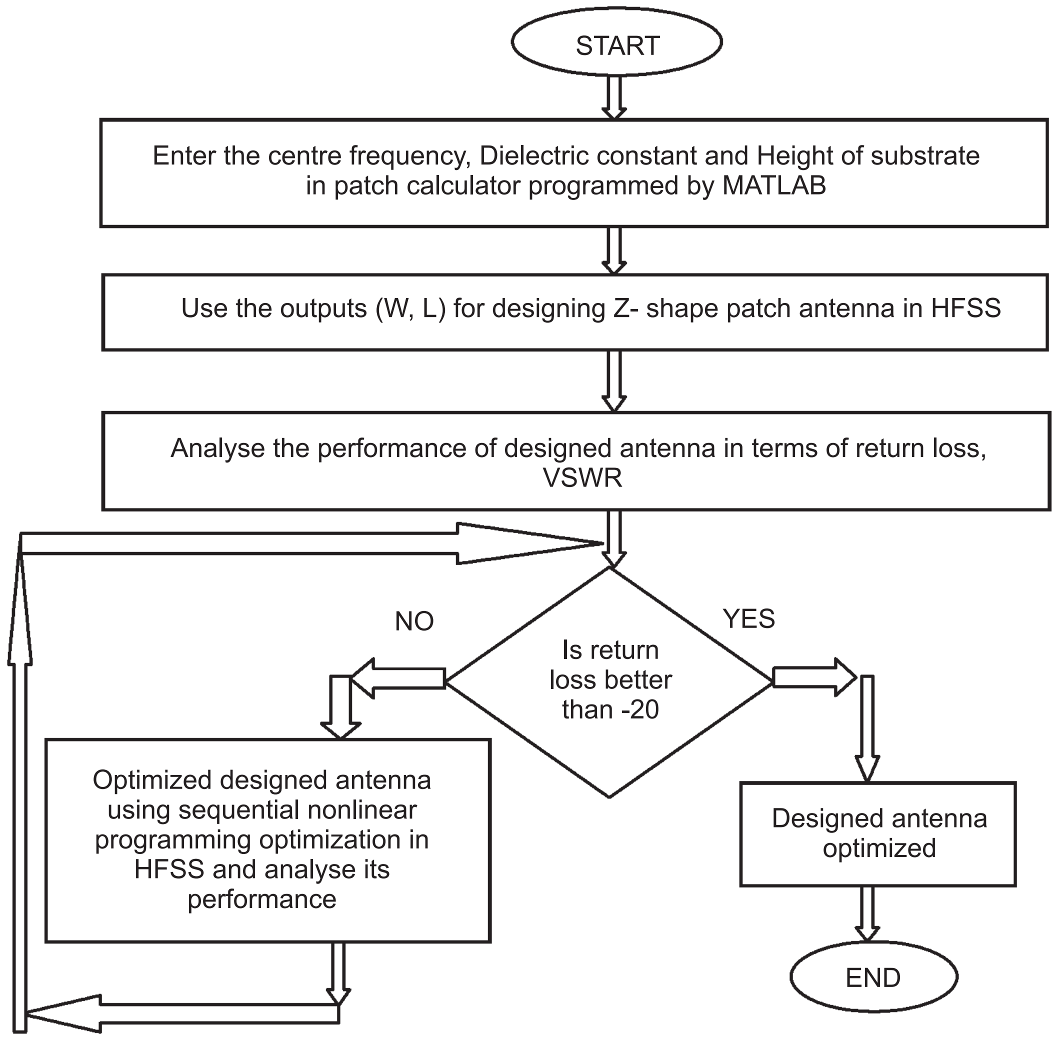

Figure 3: Flow chart showing use of SNP in Z- shape patch antenna design

Return Loss : For better performance at resonance frequency the return loss should be minimal. The return loss plot for the designed Z- shaped patch antenna are shown in fig. 4.

The optimized Z- shape patch exhibits return loss of -26.8279 dB at 3.4 GHz, -19.2961 dB at 4.25 GHz and -20. 2078 dB at 4.7 GHz. Where as the return loss plot of the un-optimized Z- shape patch antenna is -17.82 dB at 3.35 GHz, -17.49 dB at 4.25 GHz and -12.89 dB at 4.6 GHz.

It shows that the resonant frequency is not exactly at 3.35 GHz, 4.25 GHz and 4.6 GHz. This is in accuracy in terms of the centre frequency is removed by optimizing the Z- shape patch using sequential nonlinear programming algorithm HFSS environment. Sequential nonlinear programming algorithm is one of the EM optimization techniques integrated with An soft HFSS. This can be utilized to reduce the efforts of manual tuning of the Z- shape patch dimensions in order to achieve the desired goal.

VSWR : To describe the performance of an antenna when attached to transmission line, VSWR is used. It is the measure of how well the antenna terminal impedance is matched to the characteristic impedance of transmission line. Ideal value of SWR is unity indicating that there is no standing wave on the line. VSWR variation with frequency of the optimized and un-optimized Z-shape patch antenna is shown in fig. 5.

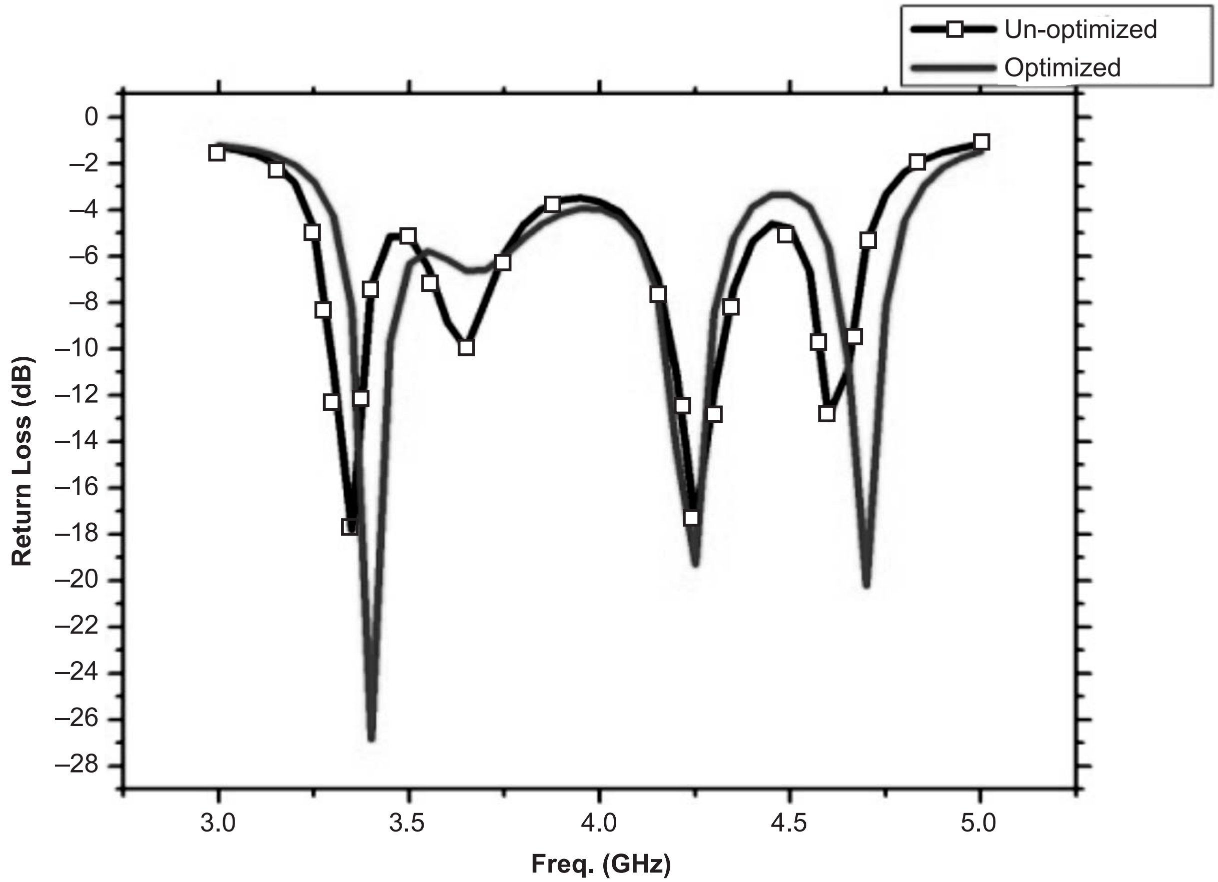

Figure 4: Return loss plot of optimized and un-optimized Z- shape patch antenna

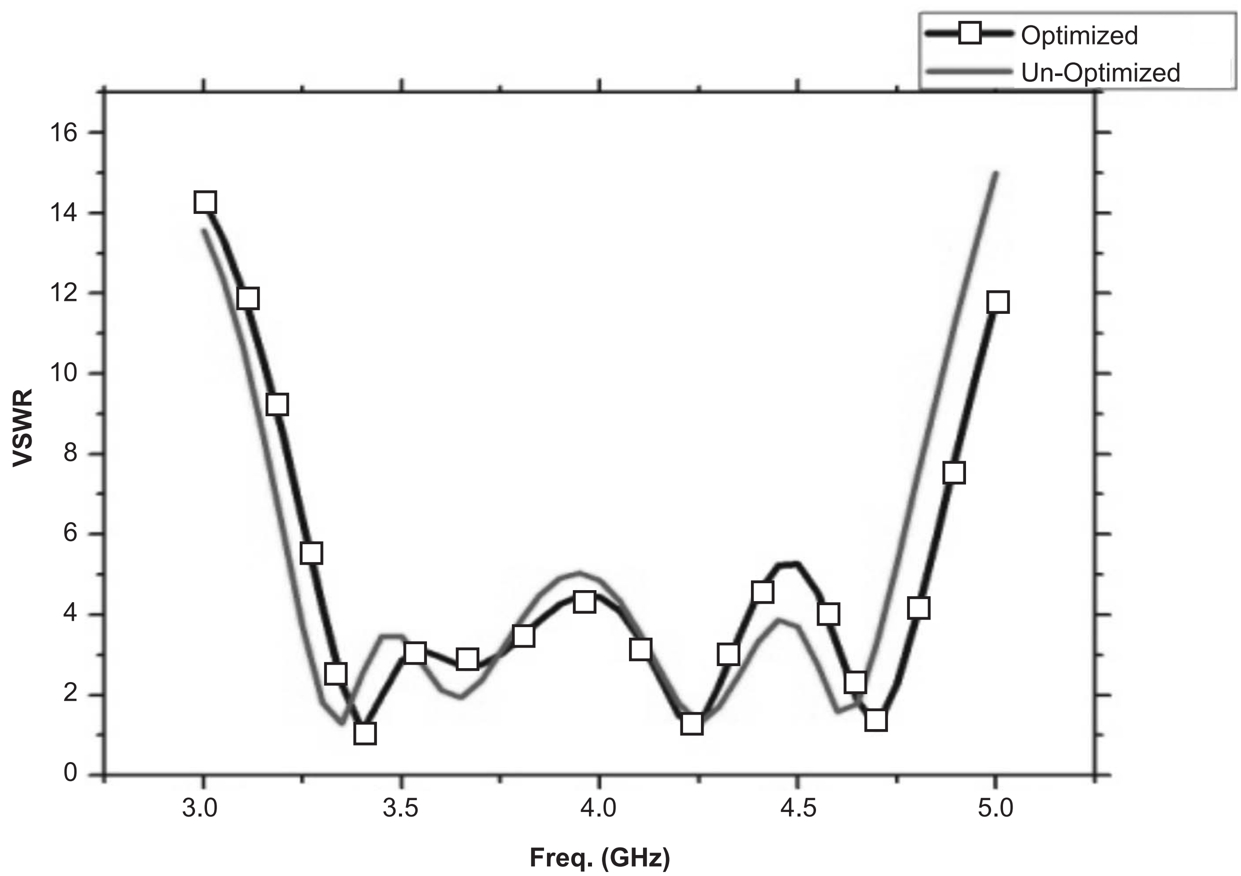

Figure 5: VSWR Vs frequency plot of optimized and un-optimized Z- shape patch antenna

From this plot it is clear that the un-optimized Z- shape patch antenna has VSWR of 1.29, 1.30, 1.58 at 3.35, 4.25, 4.6 GHz. and the optimized Z- shape patch has a SWR of 1.09, 1.24,1.21 at 3.4, 4.25, 4.7 GHz.

Directivity : The most important parameter of the patch antenna. Fig. 6 (*a*), 7(*a*) shows the radiation pattern of both un- optimized and optimized antenna. For optimized Z- shape patch antenna, the maximum directivity achieved is 6.31 dB which is 1% more as compared to the un- optimized Z- shape patch antenna. 2-D Radiation pattern polar plot for Φ = 0° at the frequencies for both optimized and un- optimized Z-shape patch antenna is shown in Fig. 6, 7.

Gain: Fig. 6 (*b*), 7(*b*) shows the radiation pattern of both un- optimized and optimized antenna.

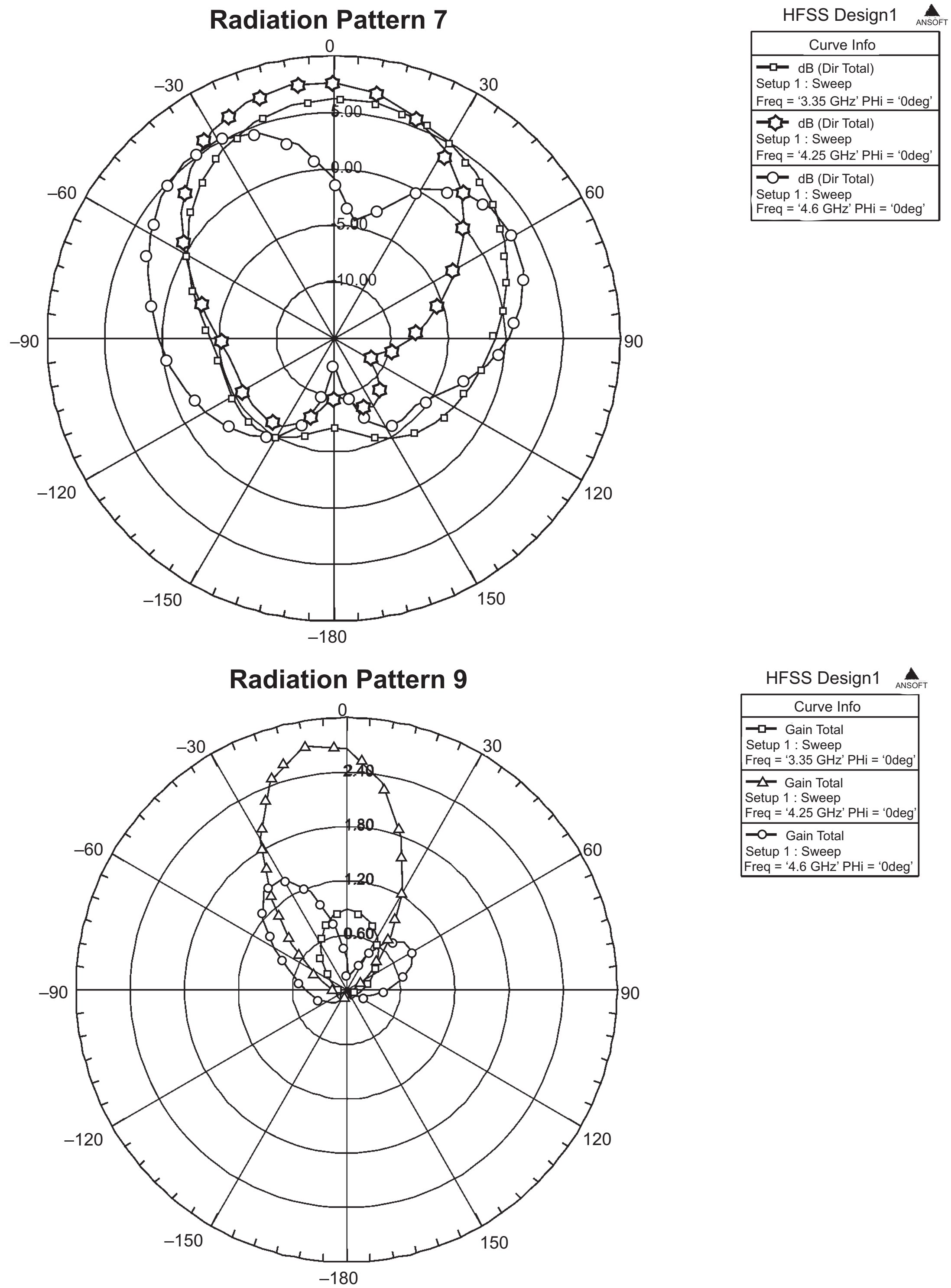

Figure 6: 2D polar plot radiation pattern (*a*) directivity (*b*) gain of un-optimized Z- shape patch antenna

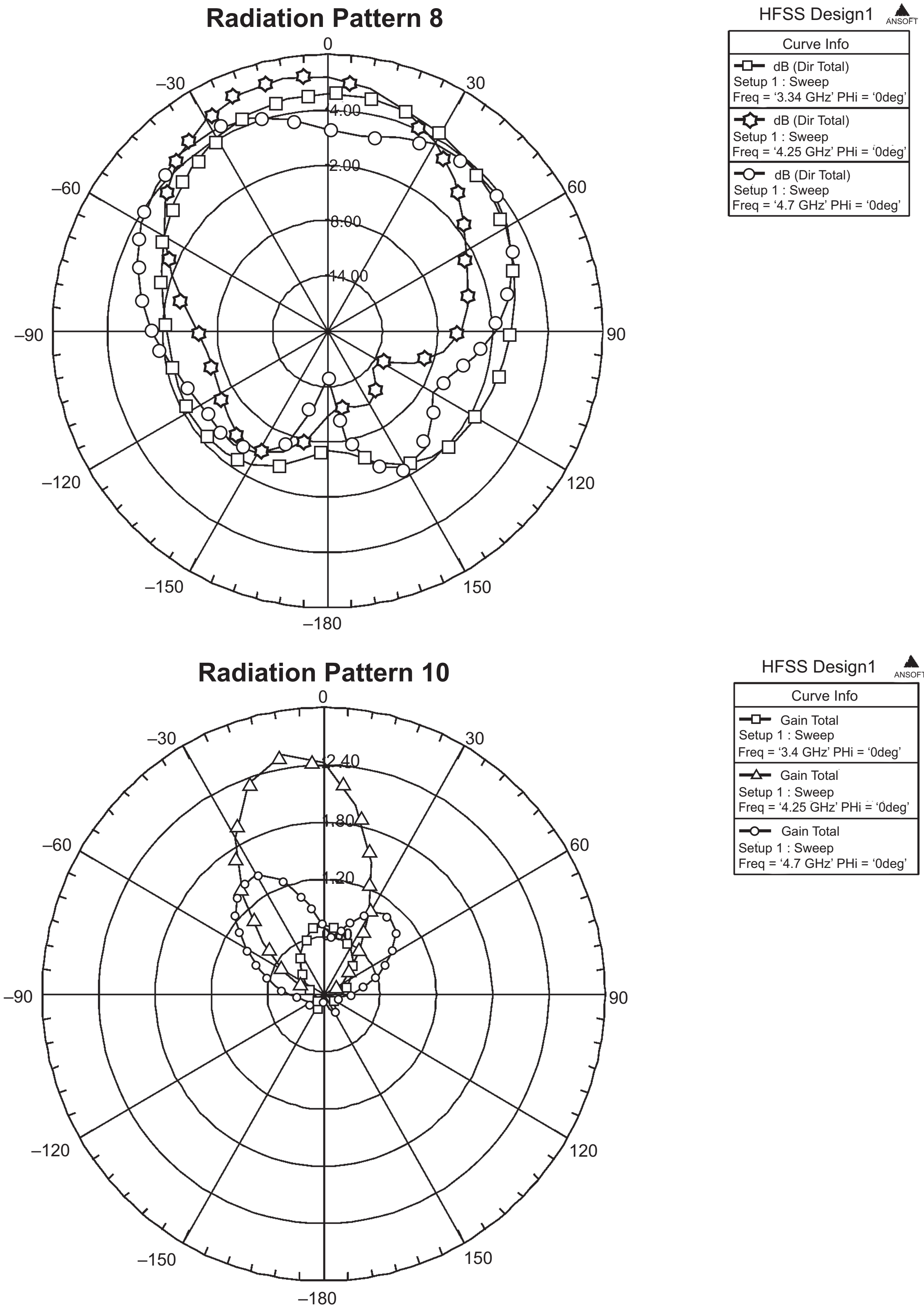

Figure 7: 2D polar plot radiation pattern (*a*) directivity (*b*) gain of optimized Z- shape patch antenna

5. V. CONCLUSION

The Z- shape patch antenna is optimized using sequential nonlinear algorithm. Now the results of both the un-optimized antenna as well as the optimized antenna are compared. These results are presented in the table 2 below. The proposed antenna Z-shape patch antenna will work in the frequency range of 3.4 GHz, 4.25 GHz, and 4.7 GHz which covers the frequency of operation of Wi-Max / S- band and C- band satellite application. That's why it is multi purpose antenna. From the table it is observed that the performance of the optimized Z- shape patch antenna using sequential nonlinear algorithm is better than the un- optimized in terms of the return loss, VSWR.

Table 2
Comparison Table

Antenna	*Frequency (GHz)*	*Return loss (dB)*	*Bandwidth (MHz)*	*VSWR*	*Directivity*	*Gain*
Z-shaped patch antenna	3.35,4.25,4.6	-17.82, -17.49,-12.89	92.7, 130.7	1.29,1.30,1.58	6.32	3.45
Optimized Z-shaped patch antenna	3.4,4.25,4.7	-26.82,-19.29,-20.20	100, 150	1.09,1.24,1.21	6.31	3.01

6. REFERENCES

1. S. Sahoo, M.N. Mohanty and R.K. Mishra, "Design of Z Shape Compact Antenna for Next Generation Wireless Network" IEEE conference, RICE- 2017(accepted)..
2. D.M. Pozar, "Microstrip antennas", IEEE Transaction on Antenna and Propagation, Vol. 80, No.1, pp.79-91, 1992.
3. R. Waterhouse, "Small Microstrip patch antenna, "Electron. Letters, Vol. 31, No. 8, pp. 604-605, 1995.
4. R Garg, P. Bhatia, I. Bahl and A. Ittipiboon," Microstrip antenna Design Handbook", Chapters 3 & 4, Artech House, Boston, London, 2001.
5. K. L. Lau, K. M., Luk and K. F., Lee, "Design of a circularly polarized vertical patch antenna", IEEE Transactions on Antennas and Propagation, Vol. 54, No.4, pp. 1332-1335, 2006.
6. N. Misran, et al., "Design and Development of Broadband Inverted E-shaped Patch Microstrip Array", American Journal of Applied Sciences, Vol.5, No.4, pp. 427- 434, 2008. Microstrip Array", American Journal of Applied Sciences, Vol.5, No.4, pp. 427-434, 2008.
7. HFSS 13 – An soft 3D full-wave electromagnetic field software. http://www.ansoft.com/products/hf/hfss.
8. M. Manzani, A. Alù, F. Bilotti, and L. Vegni, "Polygonal Patch Antenna for Wireless Communication", IEEE transanctions on vehicular technology. Vol. 53, No. 5, September 2004.
9. T.A. Milligan, Modern Antenna Design, 2nd ed., IEEE Press, John Wiley & Sons inc., 2007
10. R.J.Mailoux, J.F. Mellyenna, N.P.Kemweis, "Microstrip array Technology", IEEE Trans. Antenna Propagation Magazine, Vol.29, No. 1, pp. 25-27, 1981.
11. S. Maci and G. Biffi Gentilli, "Dual – frequency patch antennas", IEEE Trans Antennas Propagation Mag 39, pp.13-20, 1997.
12. Kumari, R.; Kumar, M, "Diamond shaped Microstrip patch antenna for Dual Band Operation" IEEE Conference IMPACT 2013.
13. Deshmukh, A.A.; Padita, V.; Colaco, R.; Doshi, R., "Dual band dual polarized modified circular microstrip antenna", IEEE Conference ISCITA 2014.
14. Singh, S.K.; Consul, P.; Sharma, K.K, " Dual band gap coupled microstrip antenna using L- slot DGS for Wireless Applications" IEEE Conference ICCCA 2015
15. Shaktijeet Mahapatra, Mihir Narayan Mohanty, "Simulation and Feed Analysis of Microstrip Antenna for UWB Communication", IEEE Conf. ICCPCT 2014, 18 – 20 Dec, 2014, Noorul Islam University, Kanyakumari, TN, India.