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Pattern Search Based Dimension Optimization of a Rectangular Inset-Fed Patch Antenna for Minimized VSWR and Return Loss

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Abstract: Microstrip Patch Antennas have made great progress in recent years and are one of the most important printed antennas for wireless applications ranging from GSM, WLAN, Wi-Fi, Wi-Max to mid and long-range RADAR tracking. Microstrip antennas have many advantages with respect to conventional antennas, which include smaller size, low cost, ease of fabrication and integration with MMIC, as well as ease of obtaining circular polarization using dual-feed or slotted patch structures. Recently, those same properties, with additional size reduction using high dielectric constant materials, have made patch antennas common in handsets, GPS receivers and other mass-produced wireless products. This paper mainly concentrates on the length and width parameters optimization of an inset-fed rectangular patch antenna with resonating frequency 3 GHz, using Hooke-Jeeves Pattern Search Algorithm for minimized VSWR as well as Return Loss. The patch antenna designs as well as optimizations are done using Ansoft HFSS 13.

Keywords: Pattern Search Algorithm, Optimization, Patch Antenna, VSWR, Return Loss

I. INTRODUCTION

An Optimization Problem usually involves minimizing a function E(x), where E(x) is named as the cost function or fitness function. That means an optimization problem can be formulated as-

$$\min_x E(x)\,, \text{where } x \in R^n \quad (1)$$

A point of consideration in any optimization problem is the concept of global as well as local minima. A global minima is a point x* for which-

$$E(x^*) \le E(x), \forall x \quad (2)$$

Similarly, a local minima is a point x* for which, there exists a neighbourhood N such that-

$$E(x^*) \le E(x), x \in N \quad (3)$$

To understand how an antenna design can be an optimization problem, let us denote an accurately simulated model of an antenna by $R_f(x)$. Typically, R_f represents evaluation of antenna performance characteristics such as Return Loss S_{11}(dB), VSWR to name a few. The vector x=[x1, x2 . . . xn] T represents the design parameters such as length/width of a patch antenna or substrate, dielectric constant of the substrate, to name a few. The vector $R_f(\mathbf{x})$ will be considered as $R_f(\mathbf{x}) = \{R_f(\mathbf{x}, f_1), R_f(\mathbf{x}, f_2) . . . R_f(\mathbf{x}, f_m)\}^T$. Here, $R_f(x, f_k)$ is the antenna model at a frequency f_k, and the frequencies f_1 to f_m represents the set of frequencies over which the model is to be evaluated.

Therefore, we can formulate an antenna design task as the following optimization problem-

$$x^* = \min_x U(R_f(x)) \quad (4)$$

Here, U is a scalar function of the design specification denoted by $R_f(x)$, which is to be minimized. $U(R_f(x))$ is also named as the objective function or cost function. **x*** is the optimum design parameters to be found.[10]

II. DIMENSIONS OF A RECTANGULAR PATCH ANTENNA

The following figure represents a typical inset-fed rectangular patch antenna. The length of a typical rectangular patch should be 0.3333λ0<L<0.5λ0, λ0 being the free space wavelength. Patch thickness should be λ<<t, meaning that the patch should be very thin. In our case, the dielectric constant of the substrate is 2.2.

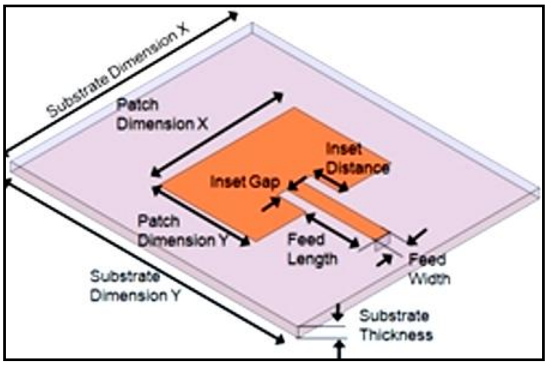

Fig. 1. Inset Fed Patch Antenna

The formulae for a typical rectangular patch antenna dimensions are as follows-

- Patch width Wp can be found by using-

$$= \frac{c}{2f\sqrt{(\epsilon_r+1)/2}} \quad (5)$$

- Patch length Lp can be found by using

$$L_p = L_{eff} - \Delta L.$$

Here, the effective length Leff can be found using-

$$L_{eff} = \frac{c}{2f\sqrt{\epsilon_{reff}}} \quad (6)$$

Similarly, the formula for effective dielectric constant ϵ_{reff} is-

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left(\sqrt{\left(1 + 12\frac{h}{W}\right)}\right) \quad (7)$$

Here, h denotes the substrate height while ϵ_r denotes the dielectric constant of the substrate.

- The differential length ΔL can be found using-

$$\Delta L = 0.412h\frac{(\epsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\epsilon_{reff} - 0.28)(\frac{W}{h} + 0.8)} \quad (8)$$

- Lastly, the formulae for substrate length and width are-

$$L_g = 6h + L \quad (10)$$

$$W_g = 6h + W \quad (11)$$

III. ALGORITHMS AND SPECIFICATIONS

A. Pattern Search as an Optimization Algorithm

Pattern Search can be used as an Optimization Algorithm when the objective function does not have a 1st and / or 2nd derivative, or they are extremely difficult to compute, which makes gradient based optimization difficult to achieve. The basic idea of a pattern search method is the search for of the objective function minimum restricted to the rectangular grid and exploration of a rectangular grid-restricted neighbourhood of the current design. If the optimizer fails to reach the current goal, the grid size is then refined and smaller step sizes are tried.[9]

Basically Pattern Search requires 4 inputs along with the optimization function to be optimized, which are-

- A starting point $x^{(0)}$
- Acceleration Factor *a*
- Initial perturbation or step change vector $\boldsymbol{P_0}$
- Perturbation tolerance vector $\boldsymbol{T} = (t_1 \ldots t_n)$, which gives the smallest perturbation for each variable.

<u>*Initialization-*</u>

- Choose initial values for $x^{(0)}$, *a*, $\boldsymbol{P_0}$ and $\boldsymbol{T}$. Initialize the perturbation vector **P** <-- $\boldsymbol{P_0}$.
- Go to Exploratory Search.

<u>*Exploratory Search-*</u>

- Use exploratory search around point $x^{(0)}$ and find an improved point $x^{(1)}$ having a better approximation of objective function.
- If exploratory search fails then reset all perturbation vectors to ½ of their initial values i.e. ***P* <-- *P/2***. If any member of **P** is now smaller than corresponding tolerance values in tolerance vector ***T***, then exit using $x^{(0)}$ as the final solution. ELSE start the exploratory search again with perturbation vector ***P* <-- *P/2.***
- ELSE if exploratory search succeeds then reset the perturbation vector to initial value **P** <-- $\boldsymbol{P_0}$.
- Go to Pattern Move.

<u>*Pattern Move-*</u>

- Obtain $x^{(2)}$ by a pattern move from $x^{(0)}$ from $x^{(1)}$. This pattern move is defined using the following formula-

$$x^{(2)} = x^{(0)} + a[x^{(0)} \sim x^{(1)}]$$

Here, *a* is the acceleration factor which multiplies the length of the improving direction.

Obtain final $x^{(2)}$ by an exploratory search around the tentative $x^{(2)}$.

- If $f(x^{(2)})$ is worse than $f(x^{(1)})$ then set $x^{(1)}$ <-- $x^{(0)}$ *a* and perform exploratory search around the starting point.
- ELSE set $x^{(2)}$ <-- $x^{(1)}$ and $x^{(1)}$ <-- $x^{(0)}$ and perform pattern move.[11]

B. Optimization Goals and Design Parameters

Here, we propose an optimization scheme to minimize return loss S11 (dB) directly or in terms of VSWR, using Patch and Substrate dimensions (length and width) as design parameters for a rectangular inset-fed patch, using Pattern Search Algorithm. Basically, a patch antenna can be optimized in 2 ways-

- Optimizing the design parameters from the scratch, when we do not have any knowledge about the value of that parameter.
- Fine tuning an already known design for enhanced performance.

C. VSWR and Return Loss as Cost Functions

Here, we will minimize S11 (dB) directly as well as in terms of VSWR. This implies that the S11 (dB) and VSWR, as a function of the length / width parameters, will serve as our cost function. The cost function in terms of VSWR is generally expressed as

$$cost = \sum_{i=1}^{N} P_i \quad (12)$$

Where P_i may be expressed as-

$$P_i = \begin{cases} (VSWR_i + 10), & Gain_i < 5\ dB \\ VSWR_i, & Gain_i \geq 5\ dB \end{cases} \quad (13)$$

We can also choose the return loss S_{11}(dB) instead of VSWR, using a cost function similar to the above, where P_i may be expressed as-

$$P_i = \begin{cases} 0, & |\Gamma_i| \leq |\Gamma_{max}| \\ |\Gamma_i|, & |\Gamma_i| > |\Gamma_{max}| \end{cases} \quad (14)$$

Where, Γ_{max} is the maximum allowable value of reflection coefficient Γ for the antenna under discussion.[10]

IV. RESULTS AND ANALYSIS

Here, we present following results and corresponding analysis-

A. Return Loss Plot of Designed Patch Antenna

As we can see from the following figure (fig 2), the return loss of S_{11}(dB) at 2.992 GHz is -20.308 dB.

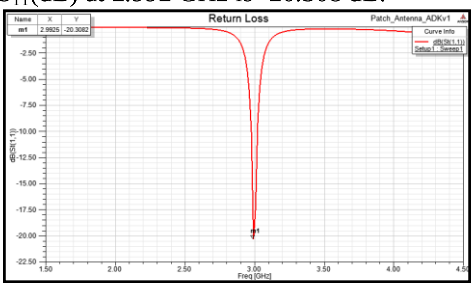

Fig. 2. Return Loss Plot of a Designed Patch Antenna

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TABLE 1:DESIGN PARAMETERS FOR THE PATCH ANTENNA

Patch Length (L)	Patch Width (W)	Substrate Length (L_s)	Substrate Width (W_s)	Frequency (f_R)	VSWR
32.9 mm	39.5 mm	98.5 mm	68.7 mm	2.992 GHz	1.21

B. Cost vs. Iterations Plot- Length Optimization

In length optimization, we use the patch length and substrate length as the optimizing parameters, to minimize S_{11}(dB), using VSWR as the cost function. We intend to find the optimal length parameters from the scratch, for enhanced performance. Here, we use a parametric analysis to find out the relationship of VSWR and patch length / substrate length. Patch length is varied from 30 mm to 35 mm, and substrate length is varied from 88 mm to 100 mm. The analysis yields a minimum VSWR of 1.13 having a patch length of 32.8 mm and substrate length of 98.6 mm. It can be verified by the following cost function plot, where the global minima can be found at iteration number 79, where the VSWR is 1.13.

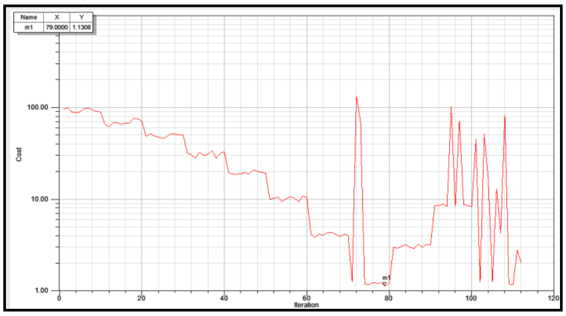

Fig. 3. Cost vs. Iterations Plot

The length optimized inset-fed patch has a return loss S_{11}(dB) of -24.23 dB at 2.992 GHz . So the length optimized patch has almost 4dB less return loss.

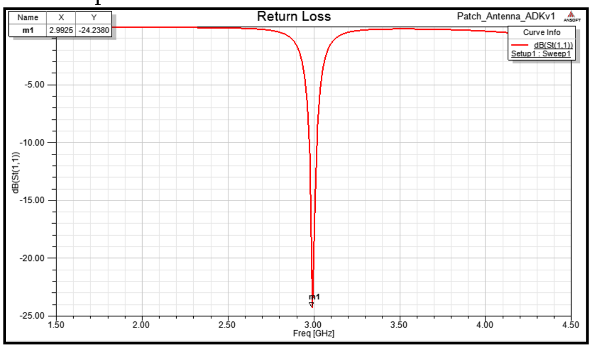

Fig. 4. Return Loss Plot of a Length Optimized Patch Antenna

TABLE 2: DESIGN PARAMETERS COMPARISON FOR A LENGTH OPTIMIZED PATCH

L	W	L_s	W_s	f_R	VSWR	S_{11} (dB)
32.9 mm	39.5 mm	98.5 mm	68.7 mm	2.992 GHz	1.21	-20.308
32.8 mm	39.5 mm	98.6 mm	68.7 mm	2.992 GHz	1.13	-24.23

C. Cost vs. Iterations Plot- Width Optimization

Similarly, in width optimization, we use the patch width and substrate width as the optimizing parameters, to minimize S_{11}(dB), using VSWR as the cost function. Here also, we intend to optimize the width parameters from the scratch. The patch width is varied from 35 mm to 40 mm, and the substrate width was varied from 60mm to 70mm. A similar parametric analysis yields a minimum VSWR of 1.03 having a patch width of 40 mm and substrate width of 67.667 mm. It can be verified similarly from the cost function plot, where a global minima occurs at iteration number 98, having a VSWR of 1.03.

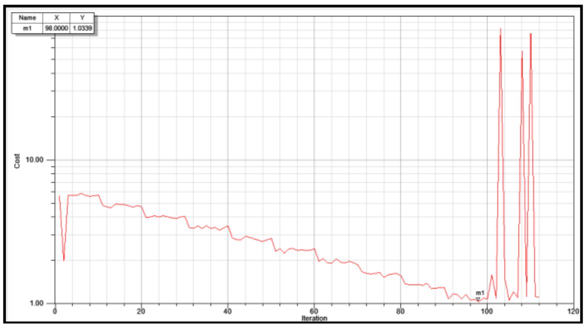

Fig. 5. Cost vs. Iterations Plot

The width optimized inset-fed patch has a return loss of -35.57 dB at 2.992 GHz. So, the width optimized patch has almost 15 dB less return loss.

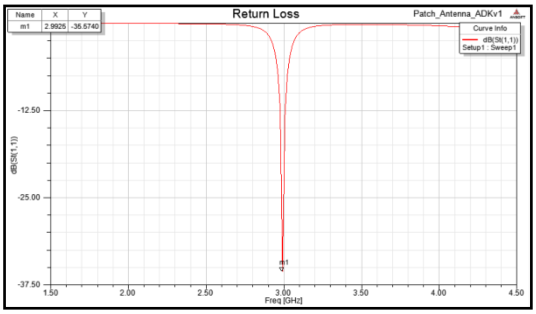

Fig. 6. Return Loss Plot of a Width Optimized Patch Antenna

TABLE 3:DESIGN PARAMETERS COMPARISON FOR A WIDTH OPTIMIZED PATCH

L	W	L_s	W_s	f_R	VSWR	S_{11} (dB)
32.9 mm	39.5 mm	98.5 mm	68.7 mm	2.992 GHz	1.21	-20.308
32.9 mm	40.0 mm	98.5 mm	67.667 mm	2.992 GHz	1.03	-35.57

D. Fine tuning the Patch Antenna for further Return Loss Minimization

We here propose a scheme to further minimize the return loss of the patch antenna by fine tuning the already optimized parameters. Here, we select the optimized values of the patch as well as substrate dimensions to

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design a new patch antenna. The design parameters are as follows-

TABLE 4 DESIGN PARAMETERS OF A NEWLY DESIGNED PATCH

L	W	Ls	Ws	f_R	S11 (dB)
32.8 mm	40 mm	98.6 mm	67.667 mm	2.992 GHz	-25.139

From the table as well as the return loss plot, we observe that the newly designed patch antenna has a return loss of -25.139 dB at 2.992 GHz. We wish to fine tune the dimensions to further minimize the return loss of the antenna, to achieve a best performance with respect to return loss.

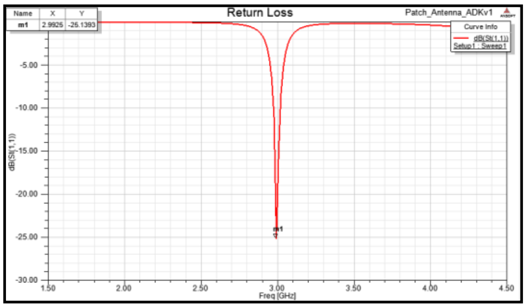

Fig. 7. Return Loss Plot of the newly designed Patch Antenna

We have fine tuned the length and width newly designed patch simultaneously, using Pattern Search Algorithm, and this time, we used the return loss S_{11}(dB) directly as the cost function. The global minima as can be seen from the plot below, occurs at iteration number 48, having a return loss of -51.09 dB. The patch length and width are 39.9 mm and 32.93 mm respectively.

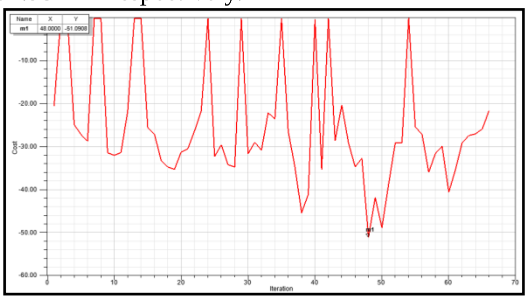

Fig. 8. Cost vs. Iterations Plot

It can also be verified similarly from the return loss plot, where, a return loss of -51.09 dB is achieved at 2.992 GHz.

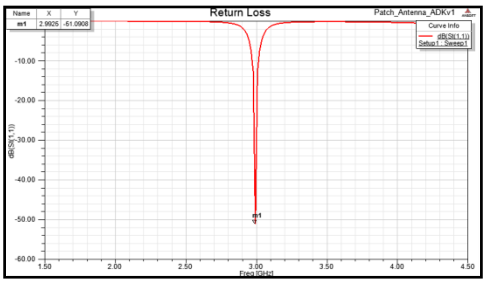

Fig. 9. Return Loss Plot of the fine tuned Patch Antenna

It may be observed that our proposed scheme has given a best performance rectangular inset-fed patch, having a return loss of about 31dB less than that of the original one. The design parameters of the final patch antenna are given in Table 5.

TABLE 5: DESIGN PARAMETERS OF A FINE TUNED PATCH

L	W	L_s	W_s	f_R	S_{11} (dB)
32.93 mm	39.9 mm	98.6 mm	67.667 mm	2.992 GHz	-51.09

The total procedure can be expressed as an algorithmic form. The algorithm is as follows-

1. Design a patch antenna using the length and width formulae given in section II. Observe the VSWR as well as the return loss at the specified frequency
2. Carry out the length optimization scheme using the patch as well as the substrate lengths as optimizing parameters, and VSWR as the cost function parameter, until global minima occurs for the given parameter ranges.
3. Design a patch antenna using the optimized length parameters. Observe the VSWR and corresponding return loss.
4. Carry out the width optimization scheme similarly, using the patch as well as the substrate widths as optimizing parameters, and VSWR as the cost function parameter, until global minima occurs for the given parameter ranges.
5. Design a patch antenna using the optimized width parameters. Observe the VSWR and corresponding return loss.
6. Design a new patch antenna using all of the optimized dimensions (patch length/width and substrate length/width), and observe the return loss.
7. Fine tune the newly design patch dimensions, to further minimize the return loss, using return loss itself as the cost function parameter itself this time, until a global minima occurs.
8. Design the fine tuned patch using the final parameter values. In our case, the fine tuned patch antenna achieves a return loss of about 30 dB less than the originally designed patch.

V. FUTURE WORKS

We wish to carry out the following works in future-

- We will study how inset dimensions, along with patch & substrate dimensions, affect the optimization scheme.
- We will carry out the entire procedure onto a probe-fed patch antenna, substituting the inset dimension parameters with the feed location parameters of the probe-fed patch, to compare its performance with that of inset-fed patch.
- We will conduct a comparative performance analysis of Gradient-Based (SQP), Gradient-Free (Pattern Search) and Evolutionary (GA) optimization algorithms for a rectangular inset-fed patch antenna with minimized return loss.

- Lastly, we intend to carry out a frequency-specific optimization scheme, where we will design a probe-fed patch antenna for minimum return loss at a specified frequency, while starting randomly with any other patch antenna having minimum return loss at any other frequency.

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BIOGRAPHIES

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Anirban Neogi was born in West Bengal, India in 1978. He did his M.Tech from Institute of Radio Physics and Electronics and M.Sc. in Electronic Science from University College of Science and Technology, Calcutta University. He is currently working as the HOD of ECE department of Dr. Sudhir Chandra Sur Degree Engineering College, Kolkata. He has started his career as a lecturer in Bengal Institute of Technology (Under Techno India Group). He has total experience of over 10 years in teaching. As a part of his research activity he got 6 international journal publications and few conference papers in the field of Nanoscience as well as in Ad-hoc networks.