Progress In Electromagnetics Research C, Vol. 86, 83–96, 2018

PSO Optimized Wideband LPDA Antenna with Non-Cross Feed Structure

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Abstract—An optimized design of Log Periodic Dipole Array (LPDA) antenna with non-cross feed structure is reported in this paper. Particle Swarm Optimization (PSO) is utilized to reduce the size and enhance the bandwidth of proposed antenna. Proposed design employs an improved feed structure of non-cross feed array antenna to avoid complexity of conventional feeding with long coaxial line and creating Co Planar Waveguide (CPW) feed. A simple FR-4 substrate with thickness of 1 mm is utilized for simulation using CST. A fitness function based on S_{11} parameter is used to achieve the optimization goal. A prototype of proposed PSO optimized antenna is developed to validate the simulation results. The proposed antenna offers higher bandwidth and significantly smaller size than cross feed LPDA antennas, with less complexity and low cost through parameter optimization, while maintaining the log periodic nature and gain.

1. INTRODUCTION

Log Periodic Dipole Array (LPDA) antenna using printed technology is now frequently used in wireless communication applications, for achieving large bandwidth, high gain and suitable radiation pattern to cover the entire frequency band. The performance of LPDA is mainly determined by length, width and spacing between dipoles, interleave factor σ, and geometry constant τ [1–3]. Besides that, the feeding mechanism also plays an important role to achieve proper impedance matching to obtain desired bandwidth and gain [4]. Moreover, the complexity of feeding mechanism also affects the measurement of radiation pattern and gain [5, 6].

A series of log periodic antennas found in literature utilize cross feed structure derived from conventional LPDA [7–13]. This cross feed structure feeds on one side of the short dipole so as to introduce a long coaxial feeding line. Therefore, such a feeding structure is disadvantageous for being integrated. Another aspect of size reduction has been achieved by using various fractal geometries such as tree, meander and Koch shape dipoles [7–11]. Use of fractals decreases the dipole lengths in vertical direction, but it introduces some negative effects, such as lower antenna gain and front to back ratio, increased cross field components and limited bandwidth. [12] has proposed UWB PLPDA, in C, X and Ku bands with an improved feeding structure of mirror coaxial cable to obtain stable phase center. This structure was not easily realizable. Further, a CPW-fed Printed Log Periodic Dipole Array (PLPDA) [13] antenna adopts complex design of creating a via hole to form a balun. Abdo-Sanchez et al. have proposed a PLPDA based on wideband complementary strip-slot element [14] which radiates by slots. It reduces the fabrication complexity by not introducing a long coaxial feeding line, but the requirement of the reflector to attain directional radiation pattern has smashed the planar design. A non-cross feed structure with balanced microstrip proposed by Kang et al. [15] avoids the introduction

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Received 1 June 2018, Accepted 1 August 2018, Scheduled 10 August 2018

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of long coaxial line, by feeding on one side of long dipole. However, it introduces some negative effects of decreased antenna efficiency and lagging additional phase shift of 180° of conventional cross feed structure, which eventually results in less bandwidth. So there is need to design a printed LPDA antenna with a simple feed structure while maintaining the advantages of planner technology, such as low weight, compact size, low cost and ease of manufacture, with enhanced bandwidth.

Recent advancement of evolutionary soft computing techniques, such as Genetic Algorithm (GA), Bacterial-Foraging Optimization (BFO) and Particle Swarm Optimization (PSO), has revolutionized the optimal designing of antenna to attain desired size and performance constraints simultaneously [16]. These methods are most reasonable for complicated problems that require monotonous and repeated analysis. PSO is a most powerful and global optimization technique which is used to optimize different continuous and discrete value problems. Hashemi et al. [17] proposed a compact optimized planar dipole antenna by using PSO, in which length, width and spacing between dipoles were chosen as optimization parameters to reduce the size of PLPDA. Differential feeding and conventional long coaxial feed have also been discussed to achieve wideband impedance matching. Different values of interleave factor (σ),and geometry constant (τ) have been obtained for each dipole using PSO. This helps in size reduction of antenna but disrupts the log periodic nature of PLPDA [17]. Further reduction in horizontal dimension of boom length along with vertical dipole lengths has been proposed by Rajendran and Menon by introducing Split Ring Resonators (SRR) with Koch fractal structure [18]. Koch fractal reduces the length in vertical direction while the horizontal dimension is reduced by inclusion of SRR which generates multiple resonances. Earlier, Aghdam et al. [19] proposed a sinuous antenna based on frequency independent concept of log periodic antenna applicable for direction finding systems and reflector feeds. It utilizes a complex feed structure of linearly tapered balun to provide impedance matching.

The prime contribution of this article is to design, analyze and optimize a non-cross feed LPDA antenna using a nonlinear optimization technique PSO. Antenna optimization is based on improvement in bandwidth and reduction in size. Generally, an antenna is optimized using linear method of parametric variations that employ a well-known cut and try procedure to find resonant frequency or bandwidth. This method is based on principle of radiation from conducting patch in a microstrip patch antenna. Commonly used methods of enhancement in bandwidth and size reduction utilize the fact of altering current distribution path, bending in certain directions to obtain same electrical wavelength and introducing a slot or gap in conducting patch material. This type of optimization requires a tedious and rigorous analysis using a simulation tool. PSO is an effective and robust algorithm inspired from natural behavior of searching food by honey bees and birds. It searches the best fitness value within a population space in a nonlinear manner. This makes fast convergence of solution space with less complexity. So this paper provides an effective way to design and optimize a non-cross feed LPDA antenna using PSO.

2. DESIGN AND OPTIMIZATION OF LPDA WITH NON-CROSS FEED STRUCTURE

The simple design of a non-cross feed LPDA based on design parameters proposed by Kang et al. [15] is used for the analysis in this paper. Referred non-cross feed LPDA has been fabricated using an FR4 substrate of thickness $h = 1\,\mathrm{mm}$ with dielectric slab area of $56\,\mathrm{mm} \times 40\,\mathrm{mm}$. The operating bandwidth of Kang's antenna is 4.2–9.2 GHz with maximum measured gain of 8.5 dBi. The antenna structure of Figure 1 with $N = 12$ elements is then optimized using particle swarm optimization technique to reduce the size and enhance the bandwidth of reference antenna [15].

The proposed antenna is fed by a coaxial SMA connector through the edge. A strip line connected with upper dipoles is soldered to coaxial pin of SMA connector while lower strip line is connected with ground of connector. For simulation purpose waveguide port is used as shown in Figure 2.

The performance of this antenna is greatly influenced by several parameters, such as scale factor (τ), spacing constant (σ), half length of largest dipole (L_1), width of largest dipole (W_1), feed length (k) and number of dipoles (N). Initial values of these parameters can be calculated from traditional

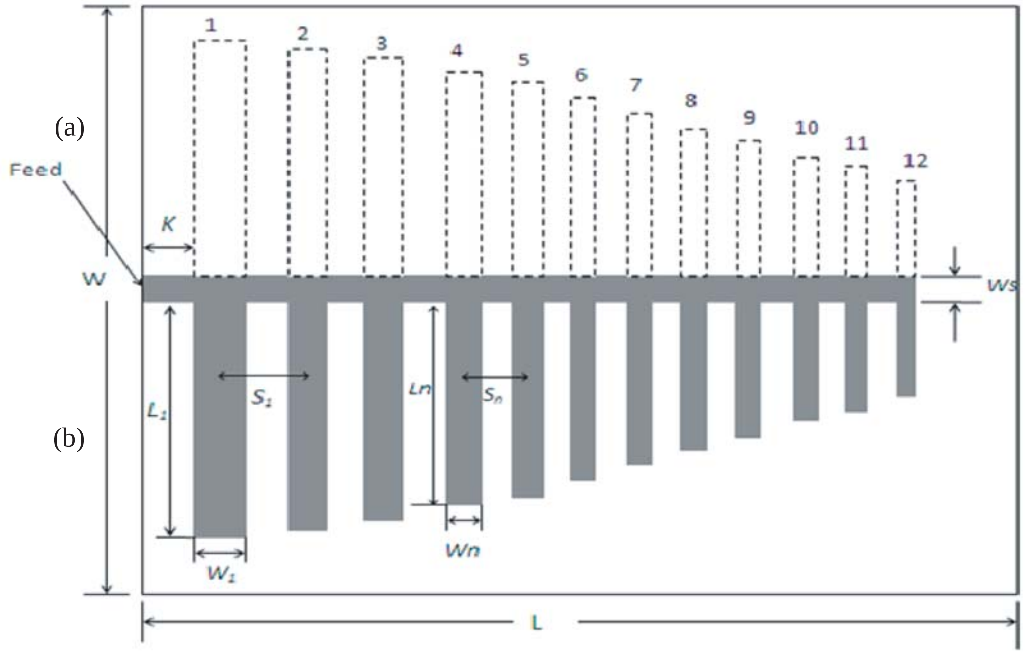


Figure 1. Schematic layout of LPDA antenna with non-cross feed structure. (a) Shaded lines (upper layer). (b) Blanked lines (lower layer).

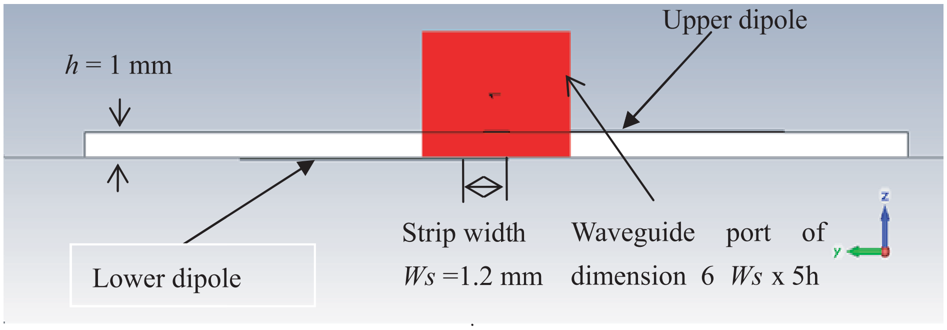


Figure 2. Geometry of waveguide port used for simulation in CST.

equations of LPDA [20, 21] as given by Equations (1)–(6).

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \times \left(\frac{1}{\sqrt{1 + \dfrac{10 \times h}{Ws}}} \right) \tag{1}$$

$$L_1 = \frac{C}{f_{\min}} \times \sqrt{\varepsilon_{eff}} \tag{2}$$

$$\tau = \frac{L_n}{L_{n-1}} = \frac{W_n}{W_{n-1}} = \frac{S_n}{S_{n-1}} \tag{3}$$

$$\sigma = \frac{S_n}{4 \times L_n} \tag{4}$$

$$Z_0 = \frac{\eta_0}{\pi} \times \left[\ln\left(\frac{L_1}{a_1}\right) - 2.25\right] \tag{5}$$

$$W_1 = \pi \times a_1 \tag{6}$$

As shown in Equation (2), length of the longest dipole L_1 is determined by the lowest operating frequency $f_{\min}$ and effective dielectric constant $\varepsilon_{\mathit{eff}}$ as determined by Equation (1). Effective dielectric constant ($\varepsilon_{\mathit{eff}}$) is dependent on the height of substrate (h) and width of feeding line Ws as shown in Equation (1). The width of parallel strip feed line (Ws) is calculated to match the required impedance of $50\,\Omega$ of SMA connector. For this purpose, a $25\,\Omega$ standard microstrip with substrate height of $h/2$ is designed using calculations given in [12]. Accordingly, the calculated value of $Ws = 1.2\,\text{mm}$, which determines the value of $\varepsilon_{\mathit{eff}} = 3.2564$ for substrate height of $h = 1\,\text{mm}$. To calculate width of the longest dipole W_1, the radius of equivalent cylindrical dipole (a_1) is determined by using Equation (5) of average characteristic impedance Z_0. Then planar width W_1 is calculated using Equation (6) to provide impedance matching with feed line so as to obtain wide bandwidth. Length and width of other dipoles and spacing between them are determined by well-known equations of scale factor, τ and spacing constant, σ as shown in Equations (3) and (4).

2.1. Implementation of PSO Algorithm

Particle Swarm Optimization (PSO) is one of the population based random optimization techniques based on the traveling behavior and intelligence of swarms [22]. In recent years, this technique has been successfully applied to antenna design and produces remarkable results. Each individual in the swarm is known as a particle or agent moving through the n-dimensional solution space defined for the problem being optimized [23]. While moving through the solution space each particle attains a position according to a certain function or method that calculates the wellness of a position. This function is called fitness function. So the proposed LPDA (Figure 1) with non-cross feed is optimized using PSO by calculating the fitness of particle in solution space in order to reduce the size and enhance the bandwidth while maintaining the appreciable gain over the entire bandwidth.

2.1.1. Defining Solution Space (Optimization Space)

As the performance of this antenna is greatly influenced by five parameters, namely, scale factor (τ), spacing constant (σ), length of longest dipole (L_1), width of the longest dipole (W_1) and width of feeding line (W_s), these parameters define optimization space for PSO. So the set of five design parameters define the particle in this case. Scale factor, τ ranges from 0.84 to 0.90, because too high value of τ increases the size of structure, while a value too low will cause reduction in directive gains. The spacing constant σ is varied from 0.10 to 0.20 to maintain a proper coupling between dipole elements along with also achieving the goal of size reduction. Length of the first dipole L_1 decides the lower cutoff frequency $f_{\min}$ as shown in Equation (2); hence it is varied in the range of 12.4 mm–14.4 mm for the ease of flexibility and uniformity in simulation. The width W_1 plays an important role in proper impedance matching of antenna, and it is varied in the range of 0.8 mm–2 mm. Feed width W_s is calculated to match the impedance of 50 ohm SMA connector. It has been observed that feed width W_s decides the current distribution among all the dipole elements which in turn also affects radiation pattern and gain characteristics. So, feed width W_s is varied in the range of 1 mm–4 mm, to get optimum value of gain and impedance matching. Based on above mentioned facts, the selected lower and upper limits of all the five parameters are listed in Table 1, which is defined as optimization space of PSO.

2.1.2. Fitness Function Calculations

A simple fitness function based on S_{11} parameter is used to maximize the bandwidth and optimize the size of antenna structure [24]. The fitness function is defined as follows

$$Fitness = \frac{1}{n}\sum_{i=1}^{n} F(f) \tag{7}$$

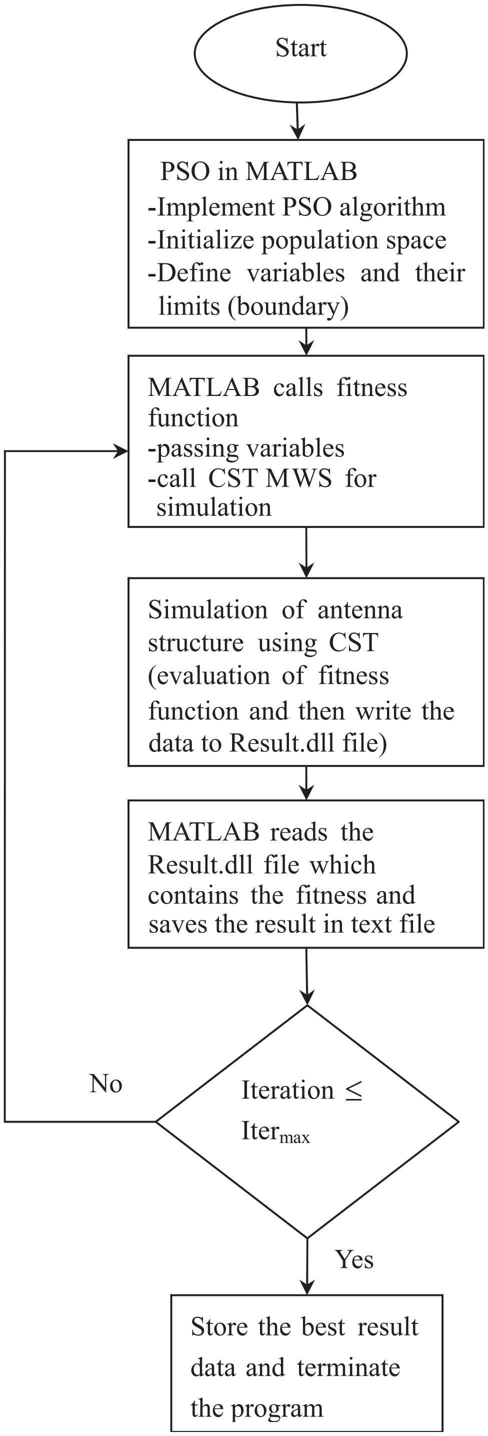


Figure 3. Flow Chart showing the steps to link the MATLAB with CST simulator.

$$F(f) = \begin{cases} S_{11}(linear) & \text{for } S_{11}(linear) \geq 0.3124 \\ 0.3124 & \text{for } S_{11}(linear) \leq 0.3124 \end{cases} \tag{8}$$

Here $n = 1000$ is the number of frequency samples over the entire bandwidth, and S_{11} (linear) indicates the reflection coefficient value in linear scale. In this case, S_{11} is truncated to the value of 0.3124 in linear scale to get the fitness function value below $-10\,\text{dB}$ in logarithmic scale.

Table 1. Optimization space for proposed PSO optimized LPDA antenna with non-cross feed structure.

Parameters	**Lower Limit**	**Upper Limit**
Length of first dipole (L_1)	12.4 mm	14.4 mm
Width of first dipole (W_1)	0.8 mm	2 mm
Spacing constant (σ)	0.10	0.20
Scale factor (τ)	0.84	0.90
Feed Width (W_s)	1 mm	4 mm

After initializing the solution space (population space) with five parameters τ, σ, L_1, W_1 and W_s and assigning their limits according to Table 1, PSO algorithm calculates fitness function every time, when CST simulates antenna structure (Figure 1) based on uniformly distributed random values of parameters. The CST simulation generates a text file which is read by MATLAB. The fitness function is calculated repeatedly in a loop, and values of personal best and global best positions of the particle are updated in every iteration according to the velocity of the particle as given in [23]. The optimization goal is to achieve large bandwidth by converging all frequency samples of S_{11} below -10 dB. Hence the optimization problem is a minimizing problem. Because of the small variations in lower and upper bounds of parameters, population size of 10 particles with 10 iterations is used in this paper. Population size of 10 is appropriate to create randomization within the lower and upper limits of variables. The number of iterations is selected according to the complexity in simulation and processor speed. The overall flowchart of PSO algorithm linking MATLAB with CST simulator is shown in Figure 3. Convergence curve of PSO algorithm is shown in Figure 4, which shows the best cost of fitness function at each iteration, and the best cost tends towards zero during iteration process.

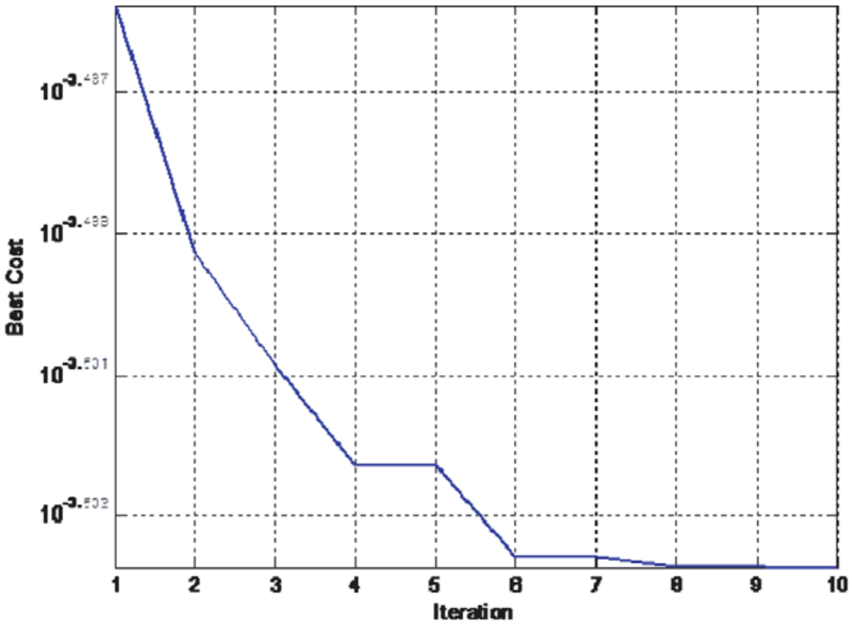


Figure 4. Convergence curve of PSO algorithm.

The optimized parameter values obtained after application of PSO by defined procedure on the optimization space of Table 1 are listed in Table 2. Based on these optimized parameter values, a complete geometry of PSO optimized non-cross feed LPDA is listed in Table 3. This antenna geometry is then simulated using CST microwave studio to obtain desired performance characteristics of reflection coefficient S_{11} (dB), realized gain and radiation pattern.

Table 2. Optimized parameters of proposed PSO optimized LPDA antenna with non-cross feed structure.

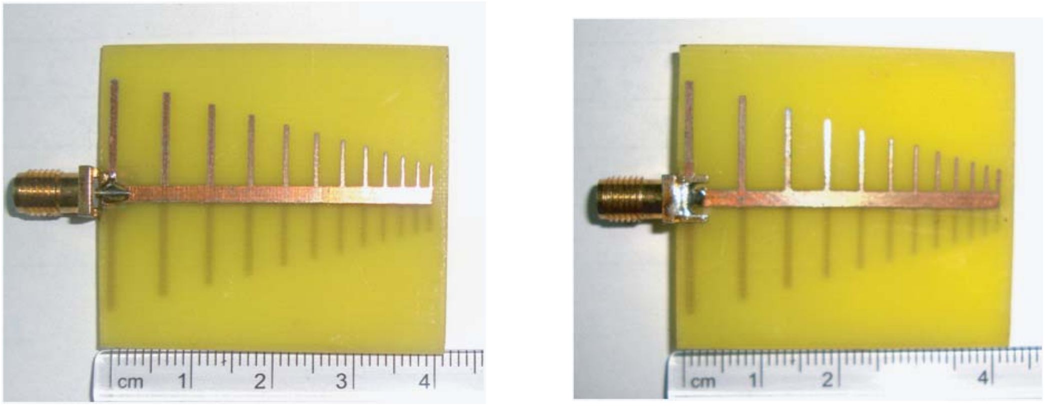
Parameters	**Optimized Value**
Length of first dipole (L_1)	14.05 mm
Width of first dipole (W_1)	1.29 mm
Spacing constant (σ)	0.11
Scale factor(τ)	0.863
Feed width (Ws)	2.08 mm

Table 3. Dimensions of proposed PSO optimized LPDA antenna with non-cross feed structure.

Dipole	**Length (mm)**	**Width (mm)**	**Spacing (mm)**
1	$L_1 = 14.05$	$W_1 = 1.29$	$S_1 = 6.182$
2	$L_2 = 12.125$	$W_2 = 1.113$	$S_2 = 5.335$
3	$L_3 = 10.464$	$W_3 = 0.96$	$S_3 = 4.604$
4	$L_4 = 9.030$	$W_4 = 0.829$	$S_4 = 3.973$
5	$L_5 = 7.793$	$W_5 = 0.715$	$S_5 = 3.429$
6	$L_6 = 6.725$	$W_6 = 0.617$	$S_6 = 2.959$
7	$L_7 = 5.804$	$W_7 = 0.532$	$S_7 = 2.553$
8	$L_8 = 5.009$	$W_8 = 0.459$	$S_8 = 2.203$
9	$L_9 = 4.322$	$W_9 = 0.396$	$S_9 = 1.902$
10	$L_{10} = 3.730$	$W_{10} = 0.342$	$S_{10} = 1.641$
11	$L_{11} = 3.219$	$W_{11} = 0.295$	$S_{11} = 1.416$
12	$L_{12} = 2.778$	$W_{12} = 0.255$	—-

3. RESULTS AND DISCUSSIONS

After PSO optimization, a prototype of proposed LPDA antenna with a non-cross feed structure is developed according to the dimensions of Table 3 and shown in Figure 5. A simple FR-4 substrate



(a) (b)

Figure 5. Prototype of Proposed PSO optimized LPDA with non cross feed structure. (a) Top layer. (b) Back layer.

with thickness of 1 mm and $\varepsilon_r = 4.4$ is used for this purpose. The simulated and measured results of reflection coefficient S_{11} (dB), realized gain (dB) and radiation pattern are depicted in Figures 6–9. It is observed that measured bandwidth is enhanced by 2 GHz, covering frequency range from 3 GHz to 10 GHz with maximum measured gain of 7.4 dB. Measured and simulated results are matched satisfactorily and validate the optimization of antenna using PSO. There is a slight shift of lower and upper cutoff frequencies in measurement. These differences may be due to the effect of SMA connector and mismatching tolerance.

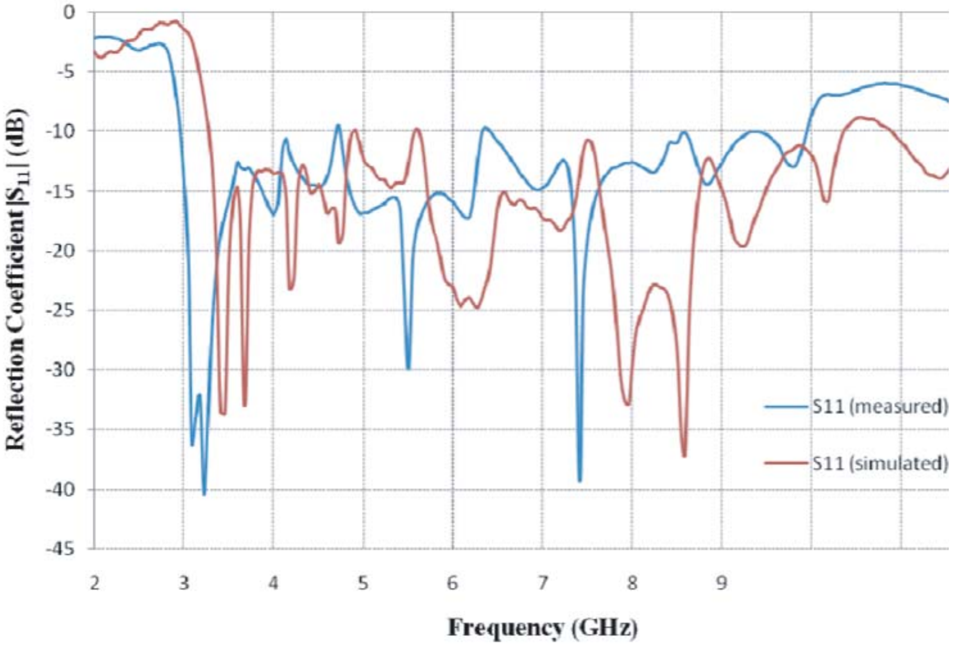


Figure 6. Simulated and measured values of reflection coefficient $|S_{11}|$ dB.

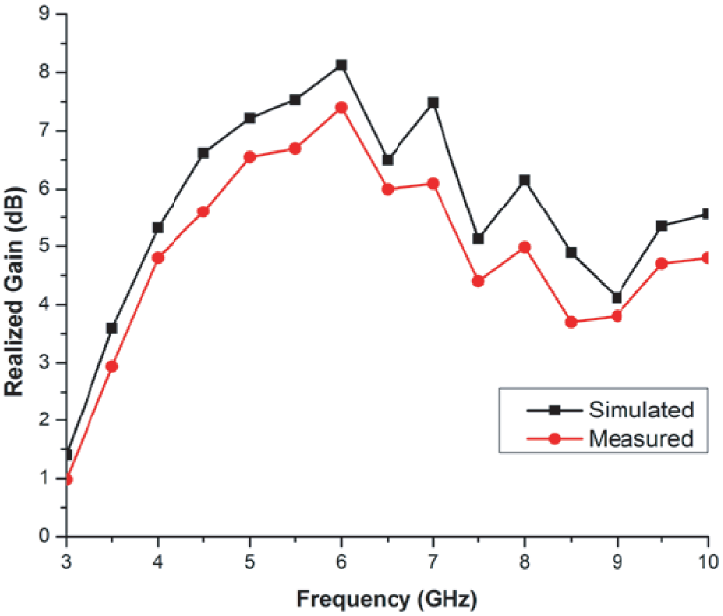


Figure 7. Simulated and measured values of realized gain (dB).

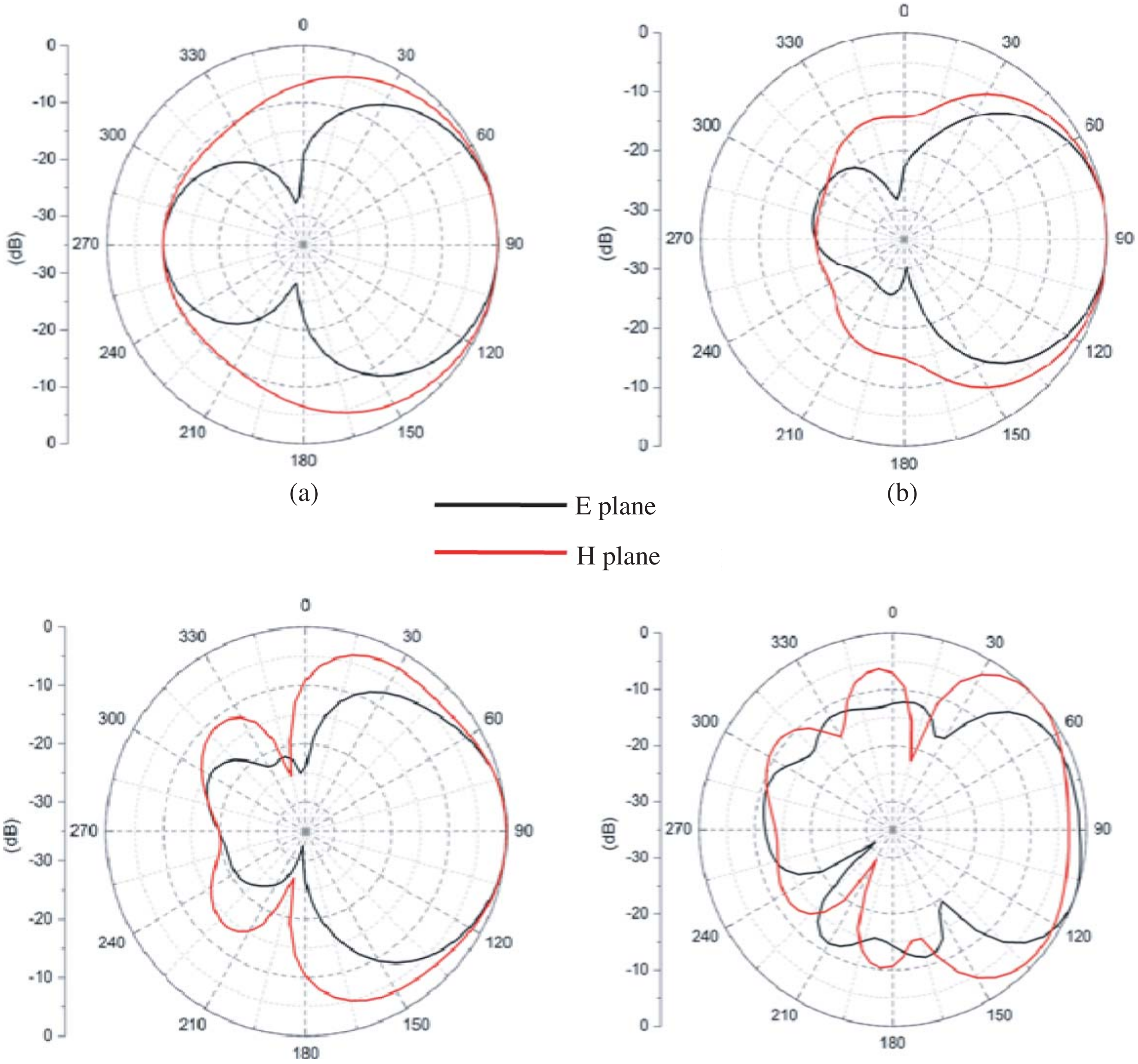
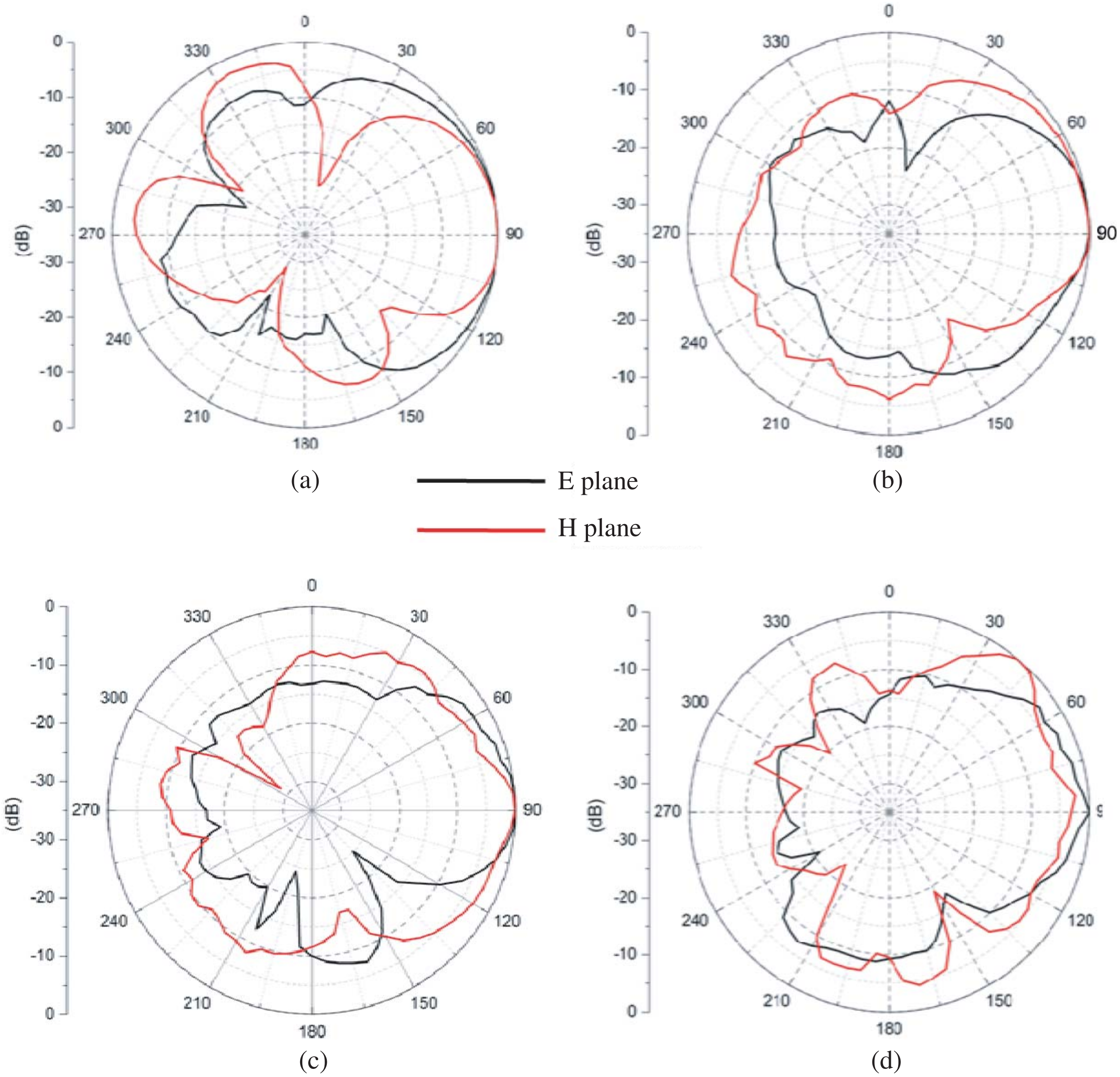


Figure 8. Simulated results of normalized radiation pattern of realized gain in E plane and H plane at various frequencies. (a) $f = 3.5\,\text{GHz}$. (b) $f = 6\,\text{GHz}$. (c) $f = 8\,\text{GHz}$. (d) $f = 10\,\text{GHz}$.

There is a slight decrement of measured gain in optimized antenna as compared to reference antenna [15], but it remains positive throughout the antenna bandwidth. The maximum measured gain of Kang's antenna [15] was 8.5 dbi, while the maximum measured gain of PSO optimized LPDA is 7.4 dBi (Figure 7). Measurement of gain and radiation pattern has been performed in an anechoic chamber, and the measured values of gain and radiation pattern of proposed antenna are shown in Figures 7 and 9. Measured gain is 1 dB less than simulated one, while measured radiation pattern also differs slightly in forming main lobe (Figures 8 and 9). There is a large variation in forming side lobes. The reason behind this variation may be that the dielectric substrate used is a simple FR4 epoxy board with great loss [15]. Its loss tangent is about the magnitude of 10^{-2}, which is more than the common Rogers, RT/duroid and ARLON AD materials (10^{-3} magnitude). The energy loss caused by it will make a difference in reflection coefficient and gain. The influence from soldering and fixture when measuring radiation pattern will affect the measured result of side lobe level. Besides, the instability of



(a) (b) (c) (d)

Figure 9. Measured results of normalized radiation pattern of realized gain in E plane and H plane at various frequencies. (a) $f = 3.5\,\text{GHz}$. (b) $f = 6\,\text{GHz}$. (c) $f = 8\,\text{GHz}$. (d) $f = 10\,\text{GHz}$.

FR-4 material will also affect the measured result of antenna radiation pattern [15].

The performance of proposed optimized antenna is compared with existing state-of-art antennas, in order to illustrate the significance of optimization algorithm. Comparative analysis is listed in Table 4. Along with improvement in operating bandwidth, a significant size reduction is also achieved using PSO. The size of reference antenna [15] is 56 mm × 40 mm, while the size of proposed PSO optimized non-cross feed LPDA is 40 mm × 40 mm. This size reduction is achieved due to the decrement in value of spacing factor (σ) from 0.15 to 0.11 and scaling factor (τ) from 0.89 to 0.863. There is increment in the longest dipole length L_1 from 13.4 mm to 14.05 mm and width of the longest dipole W_1 from 0.8 mm to 1.29 mm. The feed width W_s also increases from 1.2 mm to 2.08 mm. This increment helps to increase the bandwidth of antenna with improved input impedance matching. To compare the amount of effective size reduction, trapezoidal shape area of proposed antenna is calculated and compared with some references. Trapezoidal shape area of a compact optimized planar dipole antenna

Table 4. Comparison between the proposed PSO optimized LPDA antenna with non-cross feed structure with some reference antennas.

Antenna Type	Substrate used	Operating frequency band	Max Gain	PCB Size
Wideband complementary strip-slot Based PLPDA [14]	GML 1032 ($\varepsilon_r = 3.2$, $h = 0.762\,\text{mm}$)	2.7–8.7 GHz	5 dBi	184 mm × 100 mm
CPW Fed PLPDA [13]	ARLON AD450 ($\varepsilon_r = 4.5$, $h = 1.524\,\text{mm}$)	3–6 GHz	7.5 dBi	117 mm × 76 mm
Compact Optimized Planar Dipole Antenna [17]	RT/duroid 5880 ($\varepsilon_r = 2.2$, $h = 3.175\,\text{mm}$)	2–5.75 GHz	10 dBi	142 mm × 61 mm
Non-cross Feed PLPDA [15]	FR4 ($\varepsilon_r = 4.4$, $h = 1\,\text{mm}$)	4.2–9.2 GHz	8.5 dBi	56 mm × 40 mm
Proposed PSO optimized LPDA antenna with non-cross feed structure	FR4 ($\varepsilon_r = 4.4$, $h = 1\,\text{mm}$)	3–10 GHz	7.4 dBi	40 mm × 40 mm

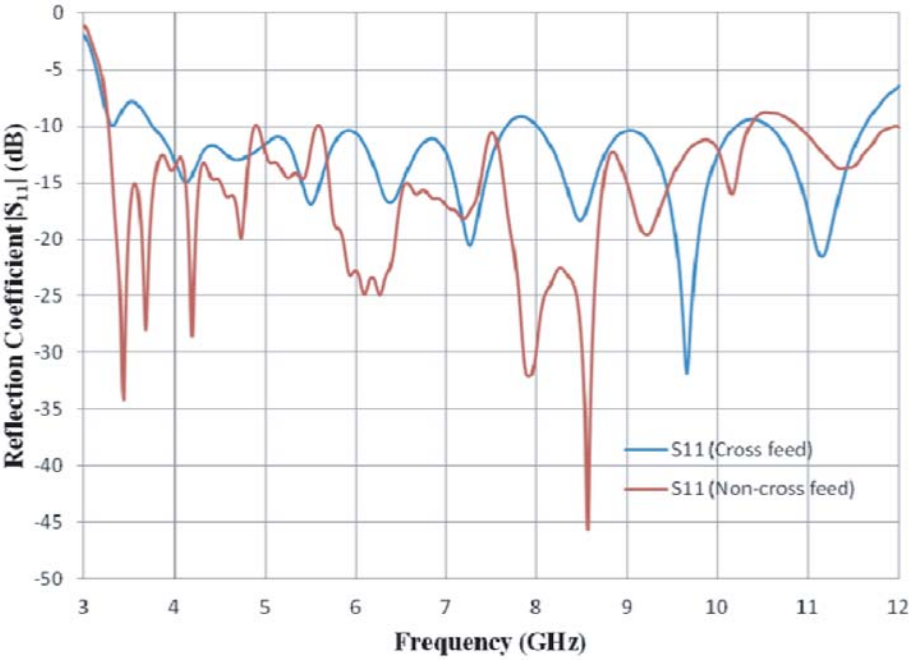


Figure 10. Simulation results of S_{11} with cross feed and non-cross feed structure.

presented by Hashemi et al. [17] is $5254\,\mathrm{mm}^2$, with working bandwidth of 2–5.75 GHz. Non-cross feed PLPDA proposed by Kang et al. [15] covers an effective trapezoidal shape area of $995\,\mathrm{mm}^2$ with working bandwidth of 4.2–9.4 GHz. The calculated trapezoidal shape area of proposed PSO optimized MLPDA with a non-cross feed structure is $718\,\mathrm{mm}^2$ with operating bandwidth of 3–1 GHz. The overall improvement in BW of proposed PSO optimized MLPDA with non-cross feed structure, to the reference antenna [15] is 2 GHz, while the net reduction in effective area is 28%. There is approximately 1 dB decrement of gain as compared to reference antenna [15], but it is acceptable as the effective area of antenna is reduced significantly with large improvement in bandwidth. Further, the gain performance of this antenna is better than recently introduced Split Ring resonators (SRR) loaded Log Periodic Koch Dipole antenna (SLPKDA) [18], which provide maximum gain of 5 dBi operating over frequency band of 0.9–2.5 GHz. It is also important to note that the proposed antenna is manufactured using a low cost FR4 substrate as compared to other reference antennas which were fabricated with low loss materials like ARLON/AD, RT/ duroid, etc. It is worth noting that PSO technique effectively optimizes the design parameters τ, σ, L_1, W_1 and W_s for given optimization space and give best fitness value, which in turn results in increased bandwidth and reduced size of antenna.

Further to compare the results of proposed antenna with conventional cross feed design, the same dimensions of non-cross feed design (Table 3) are used to simulate the structure with a cross feed structure. Simulations results of S_{11} and realized gains with cross feed and non-cross feed structures are shown in Figures 10 and 11, respectively. It has been observed that S_{11} for a cross feed structure covers approximately same frequency band as that of a non-cross feed structure, but there is reduction in realized gain of antenna with cross feed design. It is because the cross feed design fed from the smallest dipole element requires feed length of value $K = \lambda\mathrm{min}/4 = 4.165\,\mathrm{mm}$ for proper impedance matching, and we have used the same dimension of $K = 1\,\mathrm{mm}$, which causes reduction in realized gain. Impedance matching can be improved by increasing feed length $K = 4.165\,\mathrm{mm}$, but this will increase the size of cross feed structure as compared to non-cross feed structure. So non-cross feed design works better in terms of size, bandwidth and gain.

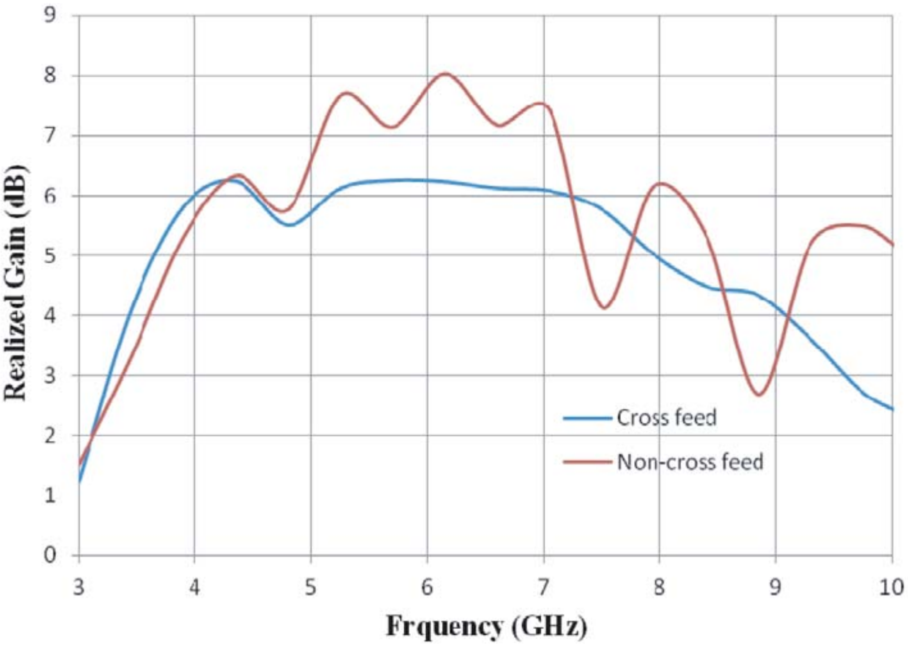


Figure 11. Simulation results of realized gain with cross feed and non-cross feed structure.

4. CONCLUSION

A detailed analysis, design and optimization of a Log Periodic Dipole Array antenna with a non-cross feed structure are presented in this article. An evolutionary soft computing technique, Particle Swarm Optimization (PSO), is employed for this purpose using five dimensional optimization space. Five sensitive geometrical parameters define the optimization space of PSO. A simple FR4 substrate is used for design and analysis using CST simulation software. Complexity of conventional a criss-cross feed structure with long coaxial line and CPW feed technique is avoided by using non-cross feed method. Further parameter optimization using PSO results in reduced size and enhanced bandwidth. A simple fitness function based on S_{11} parameter effectively is converged to give optimized value of design parameters. The proposed optimized antenna has an increment of 2 GHz in bandwidth as compared to reference antenna (4.2 GHz–9.2 GHz) and covering frequency range from 3 GHz to 10 GHz. It also offers 28% reduction in an effective area as that of reference antenna while keeping the log periodic nature and gain.

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