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Design and optimization of a non-cross feed printed log periodic dipole array antenna using particle swarm optimization

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ABSTRACT

This paper presents an optimized design of non-cross feed Printed Log Periodic Dipole Array (PLPDA) antenna using Particle Swarm Optimization (PSO) technique. An improved feed structure of **non-cross fed dipoles is chosen as reference antenna**, which avoids the complexity of conventional feeding with long coaxial line and CPW feed. A simple fitness function based on S_{11} parameter is used in PSO to achieve the goal of size reduction and bandwidth enhancement. Simulation results on CST software are verified by a manufactured prototype of proposed PSO optimized non-cross feed PLPDA antenna using FR 4 substrate with a thickness of 1.6 mm. The measured bandwidth of proposed antenna is 4.2–11.6 GHz with a fractional bandwidth of 93.6%, whereas the reference antenna covers the frequency range from 4.2 to 9.2 GHz with a fractional bandwidth of 74.6%. The effective area of the proposed design is 30% lesser than reference antenna. Proposed antenna is offering peak gain of 7.6 dBi with an average gain of 5.5 dBi in desired band. The electrical size of optimized structure is 0.53λ at center frequency. Thus, proposed antenna is offering higher bandwidth and significantly smaller size with less complexity and lower cost, while maintaining the log periodic nature and gain.

1. Introduction

As the demand of massive data communication at high speed is growing rapidly, an antenna with multi-broadband, high gain with suitable radiation pattern over the entire frequency band is desired [1,2]. Printed Log Periodic Dipole Array (PLPDA) antenna is widely used in wireless communication, to attain desired characteristics [3–10]. The PLPDA is characterized by length, width, spacing between dipoles, interleave factor σ, and geometry constant τ [3–5]. Besides that the feeding mechanism also plays an important role to achieve proper impedance matching to obtain desired bandwidth, gain and radiation pattern [6–8]. Hence PLPDA antenna with simple feed structure, low weight, compact size, low cost and ease of manufacturing is in high demand [9,10].

A lot of work has been reported in literature regarding size reduction, bandwidth enhancement, gain improvement, feeding techniques and cross polarization of PLPDA [11–20]. Qui et al. have proposed fractal antenna by utilizing the existence of self similarity and space filling characteristic to reduce the width of antenna in the direction of dipole length [11]. Improved fractal antennas with inclusion of tree structure were suggested by Baxilao et al. [12] and Lin et al. in [13] to reduce the size of antenna. The reduced size was achieved by decreasing the spacing between antenna elements which in turn lowered the antenna gain and increased the cross polarization level. Gheetan et al. [14], have investigated an amble number of shapes of dipoles to reduce the size of PLPDA by employing the first order iteration meander shape dipole to reduce the vertical height of the dipole. Meanwhile the issue of gain reduction and higher cross polarized field components retained, as in [12,13]. Anagoustou et al. have suggested a novel way for size reduction of PLPDA by using Koch shape dipoles [15]. They have decreased the dipole lengths while the length of antenna boom remained unchanged. It has resulted in lower antenna gain and front to back ratio with limited antenna bandwidth.

Researchers have shown a great interest in diverse feeding structures for antenna design. Casula et al. have presented an UWB PLPDA with a long coaxial line and mirror coaxial cable to obtain stable phase center [16]. Realize of Casula's design was very difficult due to small dimensions at microwave frequencies. A Co-Planar Waveguide (CPW) fed PLPDA was proposed by same author, in [17] to achieve wide working band of 3–6 GHz with relatively large axial dimension. Abdo Sanchez et al. have proposed a PLPDA based on wideband complementary strip-slot element [18]. Abdo's antenna radiates by slots, without introducing a long coaxial feeding line. It reduces the fabrication complexity, but the requirement of the reflector to attain directional radiation pattern has smashed the planar design.

All the above discussed antennas uses Cross Feed Structure (CFS)

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derived from conventional LPDA [11–18]. This CFS feeds on one side of the short dipole will needs a long coaxial feeding line. Such feeding structure is disadvantageous for integration of the antenna. A non CFS with balanced microstrip has been proposed by Kang et al. in [19] to avoid the introduction of a long coaxial line, by feeding on one side of long dipole. Efficiency of Kang's antenna was comparatively less due to need of an additional phase shift of $180^0$180° of conventional CFS which eventually reduces bandwidth.

Recently, introduction of evolutionary soft computing techniques revolutionized the optimal designing of antenna to simultaneously address the size and performance constraints [20]. Particle Swarm Optimization (PSO) a powerful and global techniques, which may optimize various continuous and discrete value problems. Hashemi et al. [21] proposed a compact optimized planar dipole antenna in which PSO is used to identify the optimal length, width and spacing between dipoles of PLPDA. This helps in size reduction while maintaining the log periodic nature of PLPDA [21]. Further reduction in the horizontal dimension of boom length along with vertical dipole lengths has been proposed by Rajendran et al.by introducing Split Ring Resonators (SRR) with Koch fractal structure [22]. Koch fractal leads to a vertical reduction in length while SRR generates multiple resonances to reduce the horizontal dimension. Recently, scattering performance of LPDA is studied using 3D printed technology by Yokokawa et al. which shows complexity in planar design [23]. Earlier Aghdam et al. [24] proposed a log periodic concept based sinuous antenna for direction finding systems and reflector feeds. It utilizes complex feed structure of the linearly tapered balun to provide impedance matching.

This paper presents, an optimized design of non-cross feed Printed Log Periodic Dipole Array (PLPDA) antenna using PSO. The aim of size reduction and bandwidth enhancement is achieved without affecting the log periodicity of conventional LPDA. Utilization of an improved feed structure of non-cross feed antenna avoids complexity of feeding with long coaxial line.

In rest of the paper, Section 2 describes the basic design of non-cross feed PLPDA. In Section 3, implementation of PSO algorithm to design and optimize non-cross feed PLPDA with different substrate heights is presented. Section 4 presents performance of proposed design in comparison with existing optimized antennas. Finally, conclusions are drawn in Section 5.

2. Design of Non-Cross feed PLPDA

In this work, a simple non-cross feed PLPDA antenna is chosen for design, analysis and optimization [19]. Fig. 1 shows the schematic layout of non-cross feed structure of proposed antenna. Double-sided printed circuit board structure is adopted for this purpose. Shaded area stands for the metal layer printed on dielectric slab. The proposed antenna is fed on one side of the long dipole with SMA coaxial connector for experiment, while waveguide port was used for simulation purpose. Non-cross feed PLPDA as depicted in Fig. 1 is then designed using FR4 substrates of different thicknesses $h = 1$ mm and $h = 1.6$ mm. For first design [Reference (a)] antenna proposed by Kang et al. [19] ($h = 1$ mm) is used as reference antenna for the analysis in this article. The measured operating bandwidth of Kang's antenna [19] is 4.2–9.2 GHz with maximum measured gain of 8.5 dBi. For second design substrate thickness, $h = 1.6$ mm is utilized to design the non-cross feed PLPDA which satisfies the same bandwidth and gain requirement of Kang's antenna. This second design is denoted as Reference (b), covers the frequency range of 4.07–9.66 GHz with maximum gain of 8.48 dBi.

The performance of this antenna greatly influenced by several parameters like scale factor (τ), spacing constant (σ), 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 for both designs can be calculated from traditional equations of PLPDA, as given by Eqs. (1)–(6) [25,26]. Lowest frequency (f_{min}) for both designs is set as 4 GHz. The width of parallel strip feed line (Ws) has been calculated to match the required impedance of 50 Ω of SMA connector. For this purpose a 25 Ω standard micro strip with substrate height of $h/2$ is designed using calculations given in [16]. Accordingly the calculated value of $Ws = 1.2$ mm for Reference (a) and $Ws = 4.18$ mm for Reference (b). After calculating Ws, effective dielectric constant (ε_{eff}) is calculated using following relation;

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

So the calculated value of $\varepsilon_{eff} = 3.2564$ for Reference (a) and $\varepsilon_{eff} = 3.6962$for Reference (b). Now, starting with required bandwidth of ($f_{max} - f_{min}$) GHz, where f_{max} is upper cut off frequency and f_{min} is lower cutoff frequency ,the length of longest dipole $\boldsymbol{L_1}$ is calculated by Eq. (2).

$$L_1 = \frac{C}{4 \times f_{min} \times \sqrt{\varepsilon_{eff}}} \quad (2)$$

After determining the length of largest dipole (L_1), width of dipole element (W_1) can be calculated by using the equation of average characteristic impedance Z_0 of cylindrical dipole [4] as given by Eq. (3);

$$Z_0 = 120 \times \left[\ln\left(\frac{L_1}{a_1}\right) - 2.25 \right] \quad (3)$$

where a_1 = radius of equivalent cylindrical dipole, and L_1 = half dipole length (Fig. 1). However the geometry used in this fabrication employs planar rather than cylindrical dipoles. Hence to calculate planar width of dipole, equivalent perimeters of cylindrical and thin rectangular conductors approximated as $W \cong \pi \times a$ where W represents the dipole width and $a$is cylindrical radius [7]. So the planar width of printed microstrip dipole element (W_1) is calculated by Eq. (4);

$$W_1 = \pi \times a_1 \quad (4)$$

After determining the length and width of first dipole element from Eqs. (2) and (4) respectively, other lengths, widths and spacing's can be calculated from well known equation of scale factor [26] as given by Eq. (5);

$$\tau = \frac{\boldsymbol{L_n}}{\boldsymbol{L_{n-1}}} = \frac{\boldsymbol{W_n}}{\boldsymbol{W_{n-1}}} = \frac{\boldsymbol{S_n}}{\boldsymbol{S_{n-1}}} \quad (5)$$

where $n = 1, 2, 3 \ldots N$. Another important geometrical parameter of PLPDA is spacing factor, σ which can be calculated by using Eq. (6);

$$\sigma = \frac{S_n}{4 \times L_n} \quad (6)$$

Further explanation on determination of geometrical parameters τ and σ and their effect on performance of PLPDA can be found in [27].

Complete design specifications of these two antennas are listed in Table 1. The resulting antenna structures of two designs [Reference (a) and (b)] is then simulated using CST microwave studio and performance is observed by measuring reflection coefficient S_{11} (dB) and realized gain (dB) as shown in Fig. 2(a) and (b) respectively. As shown in Fig. 2, Reference (a) covers frequency range from 4.2 to 9.2 GHz with maximum simulated gain of 9.5 dBi, while Reference (b) covers the frequency range of 4.07–9.66 GHz with maximum gain of 8.48 dBi.

3. Optimization of non-cross feed PLPDA

The antenna structure of Fig. 1, with $N = 12$ elements is then optimized using particle swarm optimization technique to reduce the size and enhance the bandwidth of two reference antennas [Reference (a) and (b)]. Here, the PSO method was applied because of its easy implementation and effectiveness [28,29]. Each technique needs to define an optimization space and a fitness function, both of which have significant effects on the optimization results [30,31]. Therefore definition