

Design of log-periodic antennas for the 1-3 GHz frequency range

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Abstract: This study presents a comprehensive analysis, simulation, and experimental evaluation of printed Log-Periodic Dipole Array (LPDA) antennas operating within the 1-3 GHz frequency spectrum. The purpose of this investigation is to develop high-performance, wideband antenna configurations using affordable FR4 substrate technology, achieving an optimal balance between electrical performance and physical compactness. The methodology/approach involves evaluating multiple LPDA models with varying element counts (8, 10, and 13 elements) using CST Studio Suite for geometric optimization, followed by the fabrication and testing of prototypes in an anechoic chamber to validate radiation patterns and return loss. The key findings demonstrate that while increasing element count enhances gain consistency and directional stability, it introduces dimensional trade-offs. Notably, the 13-element configuration achieves a maximum realized gain of 7.4 dBi and a VSWR around 1.5 across the designated band. In conclusion, this research provides critical insights into the necessary design trade-offs for modern communication applications. The practical implications of these results offer an efficient framework for engineers to select optimal antenna configurations based on specific gain requirements and spatial constraints.

Keywords: FR4, Gain accuracy, LPDA, VSWR, Wideband antenna.

1. Introduction

The rapid development of modern commercial, scientific, military, and various other communication systems has critically increased the demand for antenna systems characterized by compactness, effective operation over a wide frequency band, and high stability of electrical characteristics. With the emergence of 5G technologies, IoT networks, and advanced radar systems, the requirement for wideband performance has become a cornerstone of microwave engineering. The Log-Periodic Dipole Array (LPDA) is one of the most prominent examples of such an antenna, offering frequency-independent behavior that is vital for modern multiservice platforms.

Due to its geometric features, the LPDA ensures the maintenance of high gain accuracy over a wide frequency range, a low Voltage Standing Wave Ratio (VSWR), stability of a sharply directed radiation pattern, and, crucially, minimal signal distortion across the entire operating spectrum [1, 2]. Unlike resonant antennas, which operate within a narrow fractional bandwidth, the LPDA belongs to the class of frequency-independent antennas, where the performance remains virtually unchanged as a function of the logarithm of the frequency.

Structurally, the LPDA is composed of a sequential arrangement of dipoles. The lengths of the antenna elements and their mutual spacing vary according to a logarithmic function, defined by the design parameters τ (scaling factor) and σ (relative spacing) [3, 4]. These parameters govern the self-scaling nature of the structure; as the frequency changes, the active region moves along the antenna, ensuring that the electrical size of the radiating part remains constant relative to the wavelength. Each

dipole element functions effectively only at the frequency where its physical dimensions correspond to half the wavelength ($\lambda/2$) of that frequency [5].

This described geometry dictates that different elements of the antenna become active (resonant) at different frequencies. As a result, the entire antenna maintains efficiency across a wide frequency range. The signal supplied to the LPDA is radiated mainly by the elements that are in resonance at the given frequency, forming what is known as the “active region”. The non-resonant elements perform two significant functions in the process:

- **Impedance Matching and transition:** They help reduce signal reflection, thereby optimizing the antenna’s match with the feed line (reducing VSWR). The elements smaller than the resonant ones act as a capacitive load, while the larger ones provide inductive characteristics, creating a smooth impedance transition across the structure.
- **Directivity Enhancement:** Based on their geometric arrangement, the non-resonant elements act as passive reflectors and directors (similar to the Yagi-Uda antenna principle), which creates an additional directional effect (Directivity) and increases the overall gain [1, 6]. This interaction ensures a high front-to-back ratio, which is essential for minimizing interference in dense electromagnetic environments.

One of the significant challenges in modern antenna design is the selection of the substrate material. While high-end materials like Rogers or Teflon offer superior performance at microwave frequencies, their cost remains a limiting factor for mass-market applications. Thus, log-periodic antennas are often an uncompromising solution for many communication systems due to their structural simplicity, stability of characteristics over a wide frequency range, relatively low cost, and compactness.

The objective of this work is to create optimal configurations of a log-periodic antenna through analysis, simulation, and real-world measurements. The most common and accessible substrate, FR4 laminate ($\epsilon_r = 4.4$, $\tan \delta = 0.02$), will be used. Despite the inherent losses of FR4 at higher frequencies, its structural integrity and cost-effectiveness make it a subject of great interest for optimized LPDA designs. This paper describes the design of LPDAs that will function effectively in the 1 GHz to 3 GHz frequency range – a spectrum that encompasses critical services such as GPS, GSM-1800, and 2.4 GHz ISM bands. The paper will also compare the electrical properties (VSWR, gain, radiation pattern) of LPDAs designed with different geometric characteristics (σ and τ) to determine the sensitivity of the design to element count reduction [7, 8].

2. Analytical Design and Mathematical Modeling

The design of an LPDA involves determining the length (L_n), width (W_n), and spacing (R_n) of all its elements (Figure 1). However, it must be noted that none of the above-listed geometric characteristics are the primary result of the calculation.

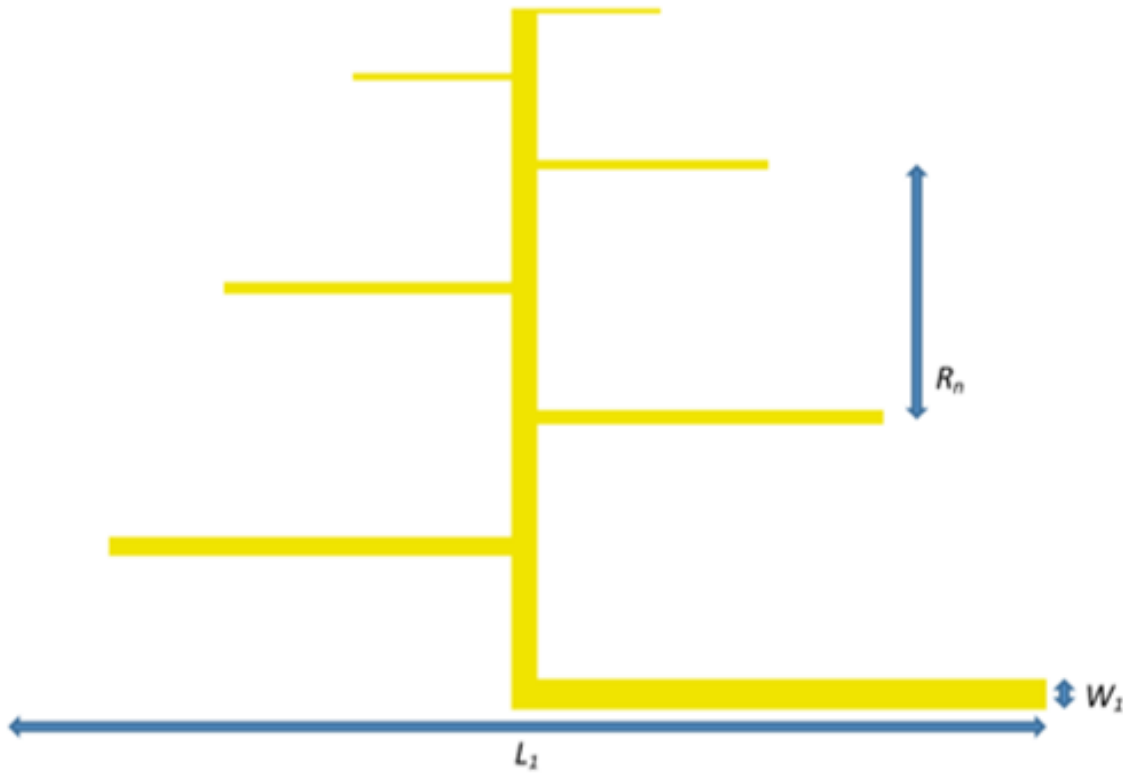


Figure 1.

General model of a Log-Periodic Antenna. L_1 is the length of the largest dipole element. W_1 is the width of the first element. R_n – the center- to-center distance between element n and its preceding element.

In the design process, the first consideration must be the operating frequency range, $f_L - f_H$. Half the wavelength of the lowest frequency (f_L) is clearly commensurate with the length of the largest, first element (L_1). The length L_1 is calculated using the formula:

$$L_1 = \frac{1}{2} \left[\frac{c}{f_{lower}} \right] \quad (1)$$

Where c is the speed of light in free space. The optimal number of elements is determined by the following formula:

$$N = 1 + \frac{\ln(B_s)}{\ln(1/\tau)} \quad (2)$$

Where N is the number of LPDA elements, B_s is the designed bandwidth, and τ is the scale factor:

$$B_s = BB_{ar} = B[1.1 + 7.7(1 - \tau)^2 \cot \alpha] \quad (3)$$

B_{ar} is the active region bandwidth, and α is half the antenna flare angle. The desired bandwidth (B) is:

$$B = \frac{f_{max}}{f_{min}} = \frac{\lambda_{max}}{\lambda_{min}} \quad (4)$$

Generally, the geometry of a log-periodic antenna is determined by three main design parameters: α , τ and σ . The relationship between them is expressed as:

$$\tan \alpha = \frac{1 - \tau}{4\sigma} \quad (5)$$

In this formula, σ represents the relative spacing. For the optimal selection of the geometric parameters τ and σ to achieve the desired gain across the entire frequency spectrum, the curves calculated by R. L. Carrel are used [3, 4]:

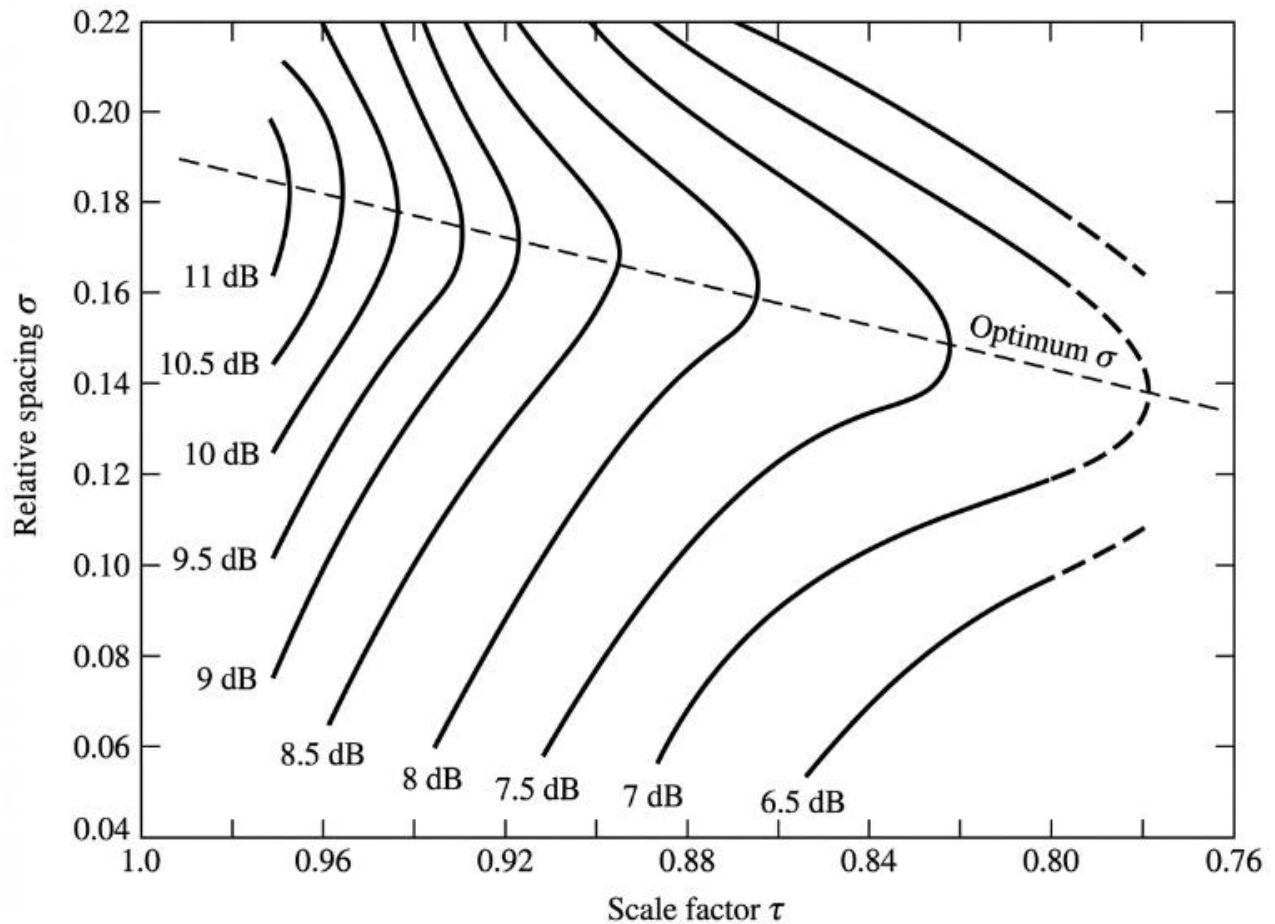


Figure 2.

R. L. Carrel's curves describe the relationship between the fundamental geometric parameters of a log-periodic antenna and the antenna's primary electrical characteristics.

Thus, if the target gain and frequency range are selected, it is possible to choose the optimal σ and τ , as well as determine the antenna flare angle and the number of elements. For a log-periodic structure, the geometric ratio τ is expressed as:

$$\begin{aligned} \frac{1}{\tau} = \frac{l_2}{l_1} = \frac{l_{n+1}}{l_n} = \frac{R_2}{R_1} = \frac{R_{n+1}}{R_n} \\ = \frac{W_2}{W_1} = \frac{W_{n+1}}{W_n} \end{aligned} \quad (6)$$

And the relative spacing σ is:

$$\sigma = \frac{R_{n+1} - R_n}{2l_{n+1}} \quad (7)$$

Using formulas (1), (2), and (7), it is possible to calculate the length, width, and mutual spacing of all elements of the log-periodic antenna [1, 7-11].

3. Antenna Design Methodology and Optimization

The design process of the proposed LPDA antennas followed a structured, iterative algorithm to ensure optimal performance across the 1–3 GHz band. While the basic geometric ratios τ and σ provide the foundation, the transition from a theoretical vacuum model to a practical microstrip-based design on an FR4 substrate requires additional considerations.

It is important to note that Carrel's classical design curves (presented in Figure 2) were originally derived for ideal, cylindrical wire dipoles operating in free space. In a printed circuit formulation, however, the antenna elements are realized as flat, planar conductive strips. To bridge this theoretical gap and utilize Carrel's curves for the initial geometric synthesis, the concept of an equivalent radius was applied. For a thin planar strip of width w , the equivalent cylindrical wire radius r_{eq} can be analytically approximated as $r_{eq} \approx w/4$. This transformation allows the initial mapping of the planar geometry into the classical wire-based mathematical framework [1].

3.1. Iterative Design Procedure

The synthesis of the 8, 10 and 13-element models was conducted according to the following analytical steps:

1. Determination of the Operating Bandwidth: The target bandwidth (B) was defined as $\frac{f_{max}}{f_{min}} = 3$. However, to account for the performance degradation at the edges of the spectrum, a “designed bandwidth” (B_{ar}) was employed, incorporating a smoothing factor based on the desired VSWR and gain levels [1, 3, 5].
2. Selection of Design Parameters: Based on the gain-bandwidth constraints, the scaling factor τ and relative spacing σ were selected for each of the three prototypes [4]. For the 13-element model, a higher τ value was utilized to ensure a denser active region, which theoretically leads to lower gain ripples.
3. Calculation of the Apex Angle (α): The convergence angle was determined using the relationship between τ and σ [1, 3]. A smaller α typically results in a longer antenna with higher gain, whereas a larger α promotes compactness at the expense of directivity.
4. Element Dimensioning: The lengths (L_n) and positions (R_n) of the dipoles were calculated. Crucially, the widths of the elements (W) were optimized to maintain a constant L/W ratio, ensuring consistent characteristic impedance across the array [6].

3.2. Substrate Effects and Effective Permittivity

While the analytical approach based on Carrel's curves provides a robust starting point, it inherently neglects the dielectric loading and the resulting increase in mutual coupling caused by the FR4 substrate. The presence of dielectric material with a relative permittivity of $\epsilon_r = 4.4$ alters the phase velocity and distorts the free-space electromagnetic field distribution around the planar dipoles. Consequently, the dimensions obtained from the classical wire model were treated strictly as an initial guess.

To account for these substrate-induced phenomena, the initial layout was imported into CST Studio Suite for rigorous 3D electromagnetic simulation. Full-wave optimization, utilizing the Finite

Integration Technique (FIT), was subsequently performed. The geometric parameters, including the scaling factor τ , spacing factor σ , and individual strip widths w_n , were systematically tuned to compensate for the dielectric loading and mutual-impedance variations, thereby ensuring the target impedance matching and radiation characteristics across the entire 1-3 GHz band.

3.3. Feeding Network and Impedance Matching

The feeding of the LPDA is implemented via a balanced transmission line (boom). The impedance of this line must be matched to the 50-ohm source. The characteristic impedance of the feeding structure (Z_0) was carefully calculated to ensure that the average input impedance of the antenna remained stable. This was achieved by optimizing the gap between the two conductors of the boom, which serves as both a structural support and a differential feed line [7].

4. Simulation and Measurement

Based on Figure 2, the first antenna was defined with $\tau = 0.88$ and $\sigma = 0.16$. The frequency range is 1 GHz to 3 GHz. The number of antenna elements is $N = 13$. The width of the feed line (center line) is $W_f = 2.76$ mm. The resulting geometric dimensions of the antenna are summarized below [3, 4].

Table 1.
Geometric dimensions of the 13-element LPDA.

Element	Length (L_n , mm)	Width (W_n , mm)	Spacing (R_n , mm)
1	144.00	2.98	0.00
2	129.75	2.58	47.12
3	112.23	2.23	40.74
4	97.14	1.93	35.24
5	83.97	1.67	30.48
6	72.63	1.44	26.37
7	62.83	1.25	22.81
8	54.27	1.08	19.73
9	47.02	0.93	17.07
10	40.67	0.81	14.76
11	35.17	0.71	12.77
12	30.43	0.60	11.05
13	26.21	0.52	9.55

Based on the geometric parameters detailed in Table 1, a control file was generated for the LPKF ProtoMat S63 PCB plotter, which was subsequently utilized to fabricate the physical prototype of the 13-element log-periodic antenna (Figure 3).

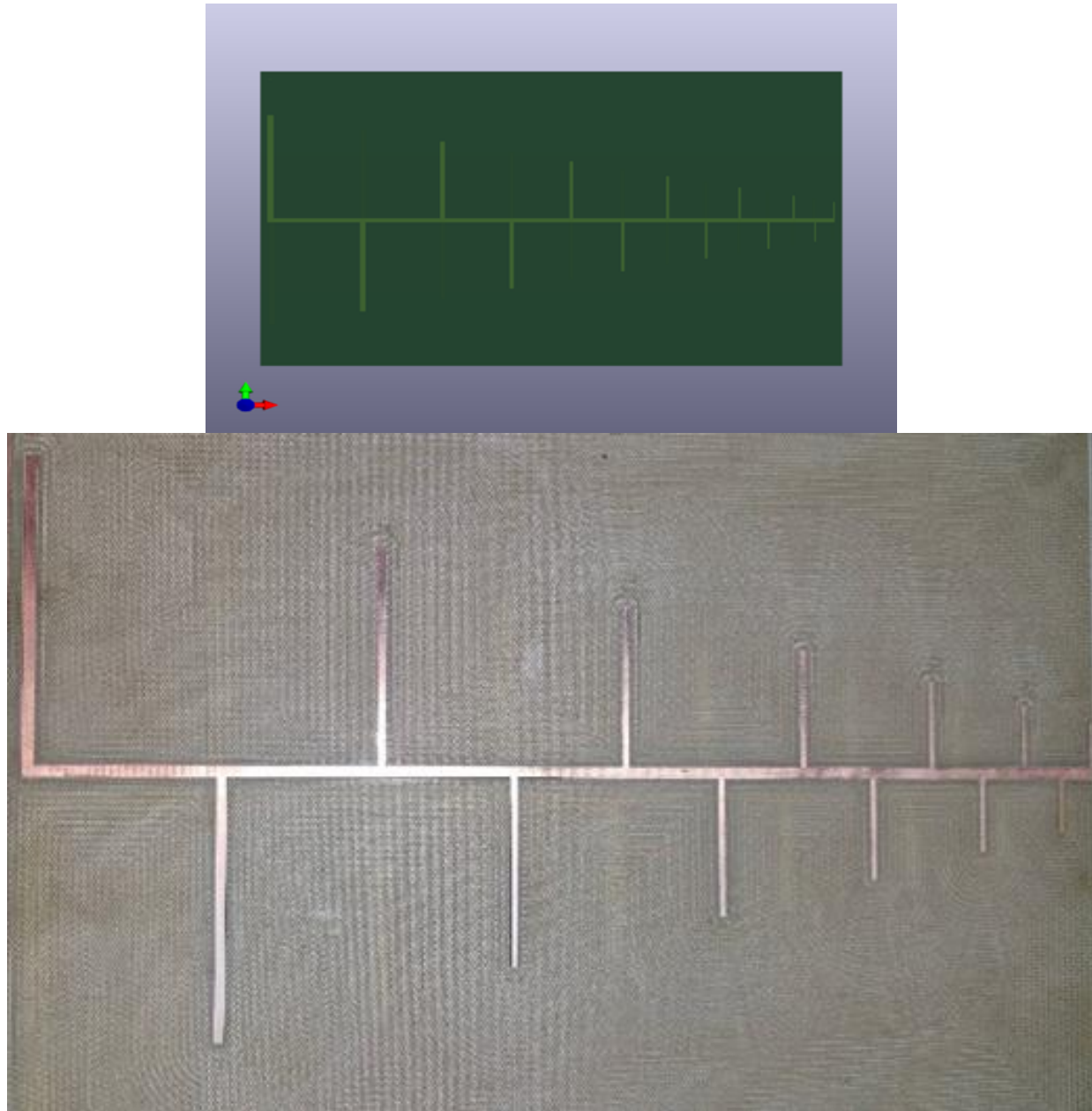


Figure 3. (Top) The control file for the LPKF S63 [PCB Plotter] shows the visualization of a 13-element log-periodic antenna. (Bottom) The visualization of the fabricated antenna. The dimensions of the substrate (textolite) are 210 x 297 mm.

4.1. *S-Parameters, VSWR*

Modeling and simulation of the given antenna were performed using CST Studio Suite. The simulation showed a good result for the S_{11} coefficient (reflection coefficient). As shown in Figure 4, the S_{11} parameter of this antenna is below -15 dB across the entire 1-3 GHz range [6].

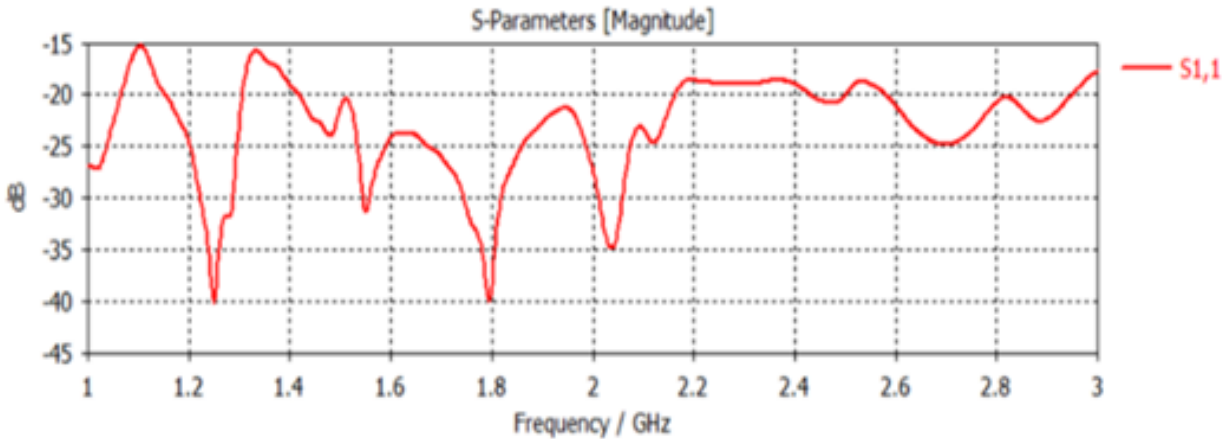


Figure 4.

The S-parameter S_{11} of the 13-element LPDA is presented as a function of frequency in the 1-3 GHz range. The maximum level of S_{11} is -15 dB.

As mentioned above, the antenna was fabricated on an FR-4 laminate ($\epsilon_r = 4.4$) and tested using an anechoic chamber (ETS-Lindgren's 2006) (Figure 5). The chamber simulates an infinite space where there are no reflections, noise, or any type of spurious radiation. Accordingly, it is possible to investigate the characteristics of the LPDA with the highest possible accuracy [12, 13].



Figure 5.

The described 13-element LPDA is positioned in an anechoic chamber (ETS-Lindgren's 2006) for measurements.

The graph below shows a comparison of the VSWR coefficients of the antenna simulated in CST Studio Suite and measured with an E5071C vector network analyzer. The data was processed in OriginPro. The black curve describes the measured VSWR, while the red curve describes the simulated VSWR. As seen from the graph (Figure 6), the real and simulated VSWR are practically less than 1.5 throughout the entire spectrum and match each other with high accuracy.

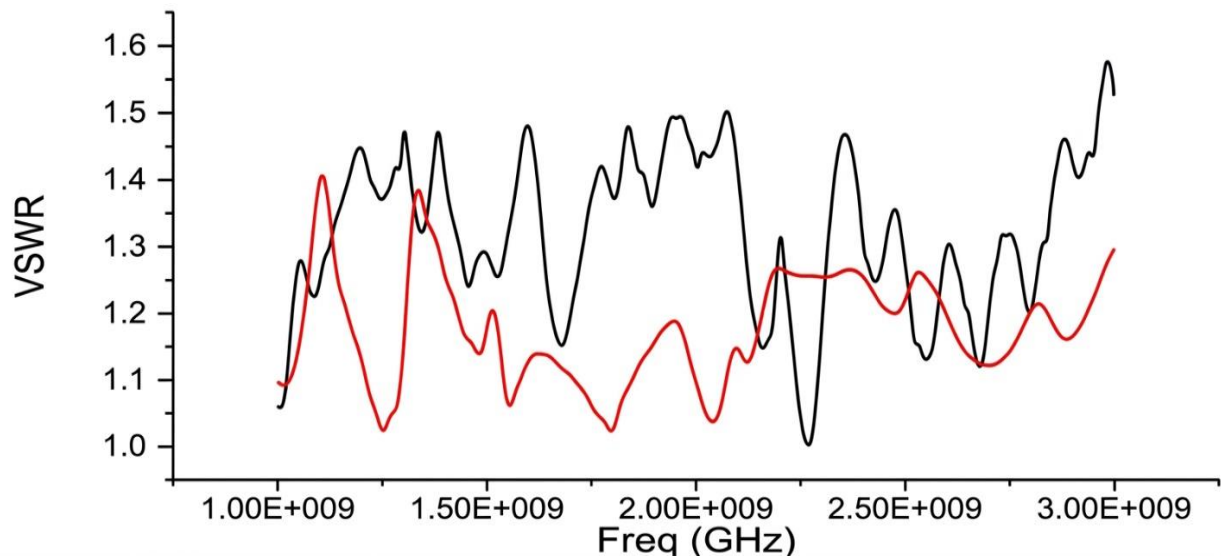
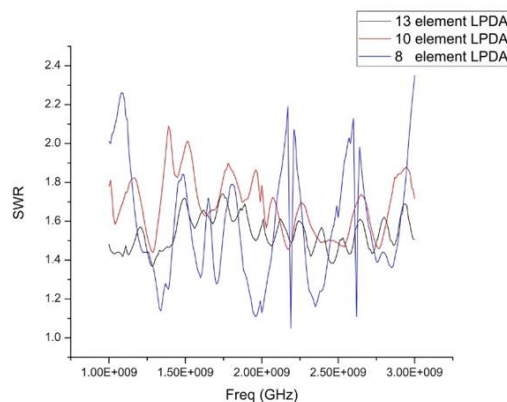


Figure 6.

The graph illustrates the frequency dependence of the VSWR in the 1-3 GHz range. The Black curve represents the measured VSWR. The Red curve corresponds to the simulation results.

The frequency dependence of the SWR for the three LPDA configurations (8, 10, 13 elements) is depicted in Figure 7(a). A clear correlation is observed between the reduction in the number of elements and the degradation of the overall SWR. Notably, however, the 8-element antenna demonstrates excellent matching at specific resonant frequencies. Figure 7(b) presents the return loss characteristics, further confirming that the 13-element configuration achieves the most stable and optimized S11 performance across the designated spectrum.



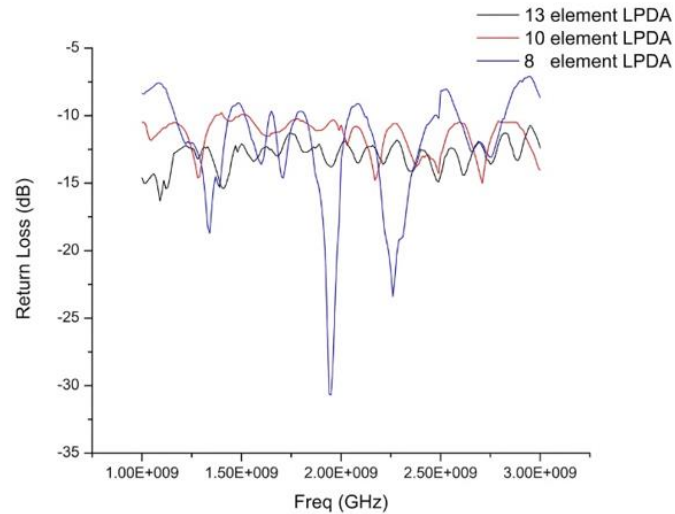


Figure 7.

(a) Frequency dependence of the SWR for all three antenna configurations (1-3 GHz range); (b) Return Loss characteristics of the three antennas as a function of frequency.

4.2. Radiation Pattern (Gain)

Figure 8 shows the simulated three-dimensional radiation pattern of the 13-element LPDA at 1.5 GHz. It is visible that the antenna is quite directional, and the radiation level is low in the side and back directions. The simulated antenna gain reaches a peak level of 7.8 dBi at 90 degrees, whereas the minimum gain drops to -34.37 dBi in the side-lobe regions.

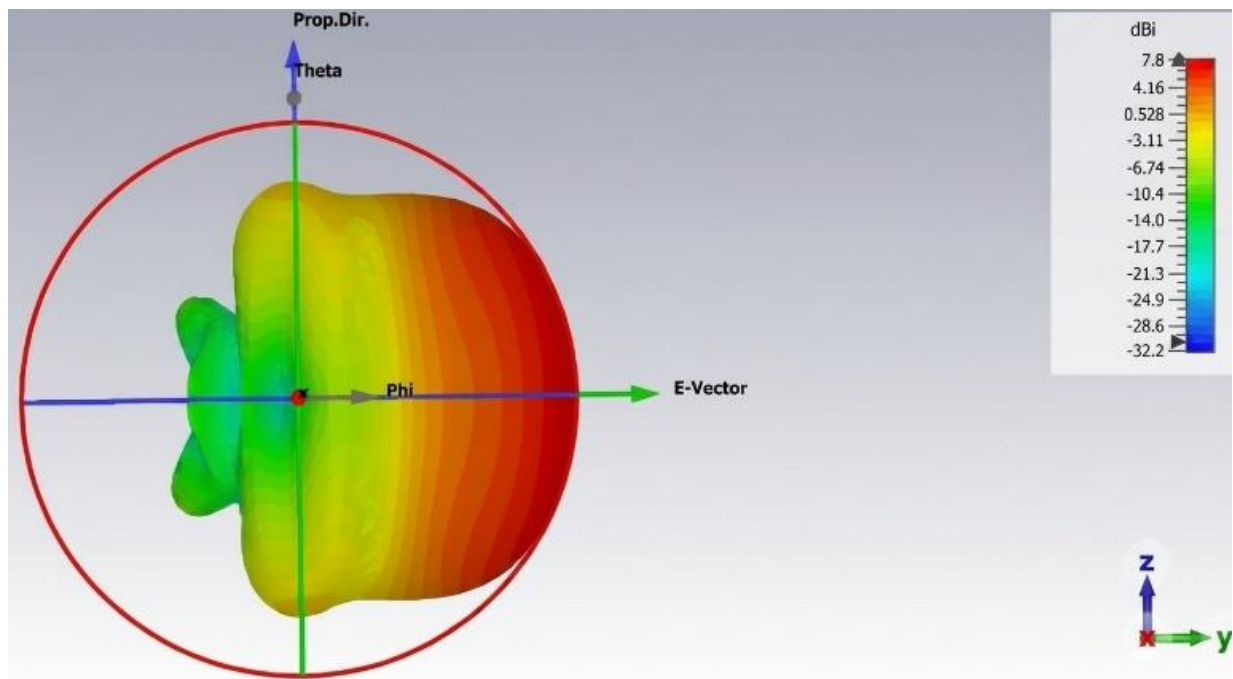


Figure 8.

Three-dimensional radiation pattern of the 13-element log-periodic antenna simulated in CST Studio Suite at 1.5 GHz.

The same can be observed on two-dimensional graphs. Below is a comparison of the simulated radiation pattern and the pattern tested in the anechoic chamber. The measurement and simulation were conducted at 1.5 GHz. At this frequency, a maximum simulated Gain coefficient of 7.8 dBi was obtained for the main lobe magnitude of the 13-element LPDA (Figure 9, solid Red). The 7.8 dBi result matches the analytical result with high accuracy and is considered better than the typical Gain characteristic for LPDAs. Figure 9 (solid Black) also shows the radiation pattern of the same antenna measured using the ETS-Lindgren 2006 anechoic chamber. The maximum Gain coefficient for the real antenna was 7.4 dBi. The difference between the maximum Gain coefficients of the simulated and real measured antennas is approximately 5%. It is also evident that the radiation pattern of the real antenna is not smooth. It appeared that both of the aforementioned differences are due to the imperfection of the real antenna and laminate geometry compared to the simulated LPDA. Probably, the $\epsilon_r = 4.4$ of the commercially available FR-4 board is not uniformly distributed across the surface [13, 14].

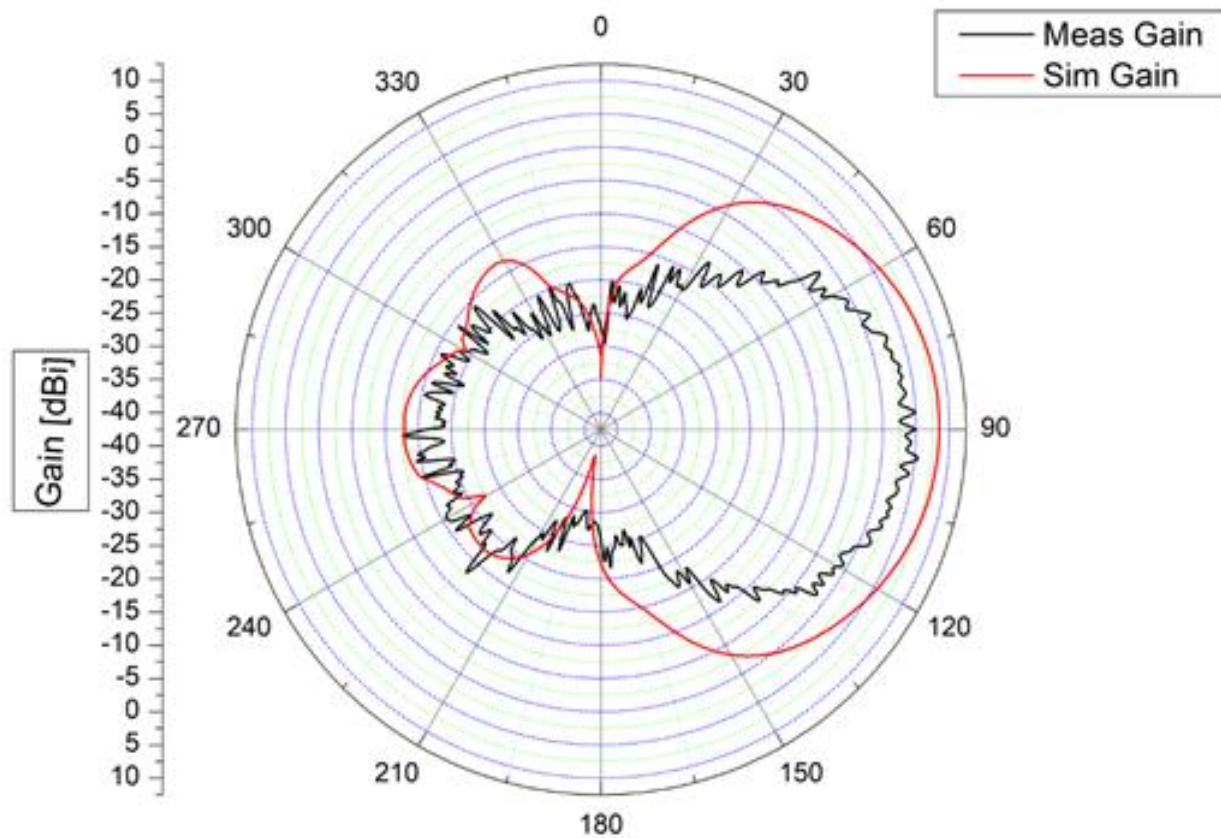


Figure 9.

Two-dimensional radiation patterns of the 13-element LPDA. A comparison of simulated results (solid red) and experimental measurements (solid black) obtained in an anechoic chamber.

Figure 10 describes the radiation pattern of the 13-element LPDA at 2.5 GHz - a comparison is provided for both the result obtained using CST Studio Suite simulation and the result obtained from real measurement. In both cases, the gain decreased within the expected range: The maximum simulated gain coefficient was 7.5 dBi, and the measured gain was 7.3 dBi. Also, both graphs show almost identical asymmetry in the back lobe of the pattern [6, 14].

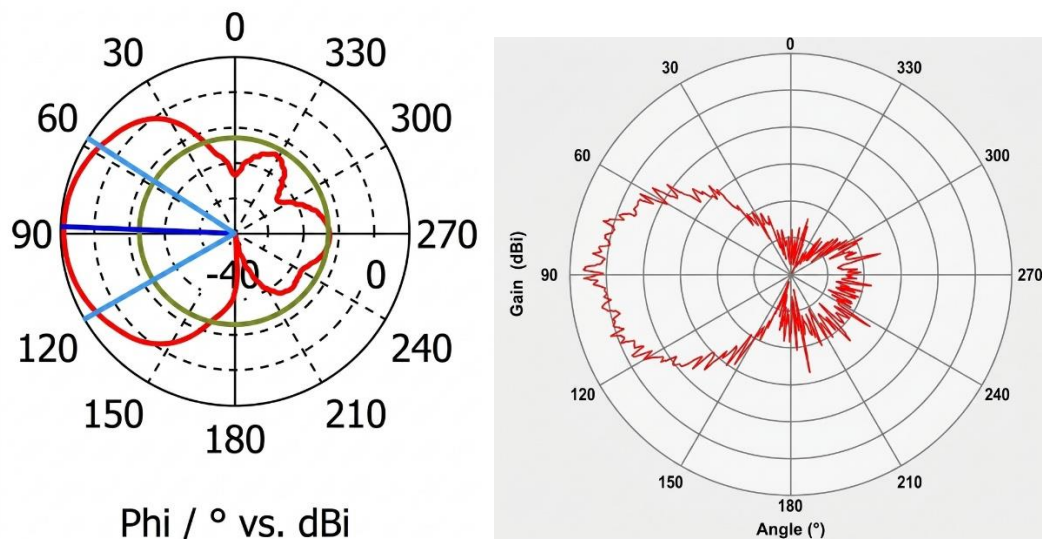


Figure 10.

On the left, the two-dimensional radiation pattern of the 13-element LPDA obtained from the simulation at 2.5 GHz. On the right is the antenna's radiation pattern obtained from the measurement at 2.5 GHz.

Figure 11 illustrates a comparison between the simulated and measured gain of the 13-element LPDA antenna across the entire selected frequency range (1-3 GHz). The discrepancy between the simulated and experimental results does not exceed 4%.

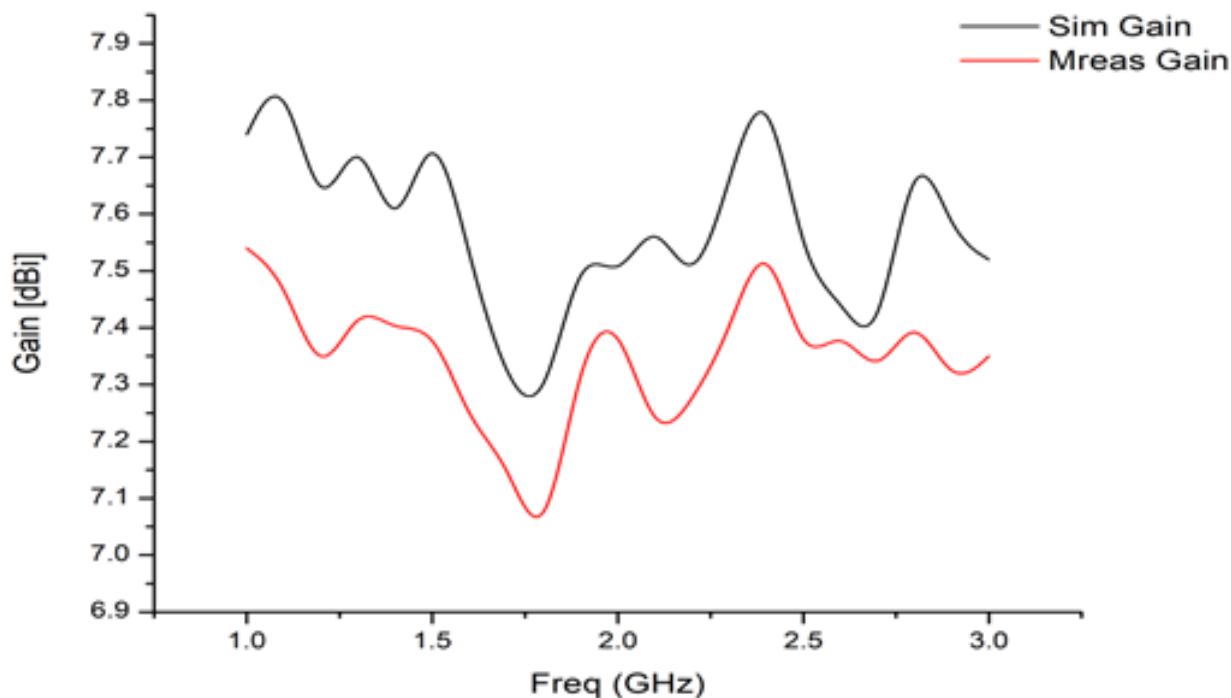


Figure 11.

The graph illustrates the simulated (solid black) and measured (solid red) gain characteristics as a function of frequency within the 1-3 GHz band.

5. Compact LPDA Alternatives (10-element and 8-element)

The dimensions of the 13-element LPDA discussed above are: length - 296.5 mm, width - 196.5 mm. Despite the antenna's good gain coefficient and quite directional radiation pattern, an antenna of such size may not be suitable for certain applications. As an alternative, two other LPDAs operating in the same frequency range were created, containing 10 and 8 elements. The table below shows the geometric characteristics of the 10-element antenna. The width of the feed line (center line) is $W_f = 2.74$ mm.

Table 2.

Geometric dimensions of the 10-element LPDA.

Element	Length (L_n , mm)	Width (W_n , mm)	Spacing (R_n , mm)
1	95.00	1.99	0.00
2	86.50	1.72	31.42
3	75.82	1.49	27.16
4	64.72	1.28	23.49
5	55.98	1.11	20.30
6	48.41	0.96	17.57
7	41.88	0.83	15.21
8	36.23	0.72	13.15
9	31.34	0.62	11.37
10	27.11	0.54	9.80

The physically realized prototypes of the 8, 10, and 13 element printed log-periodic dipole arrays implemented on the FR4 substrates are depicted in Figure 12. The comparison highlights the distinct variations in their physical sizes and structural compactness.

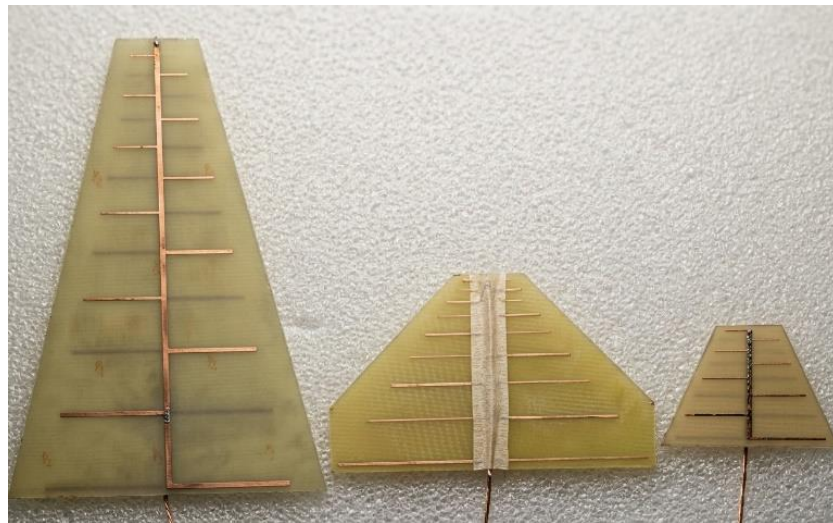


Figure 12.

From left to right: the 13-element, 10-element, and 8-element log-periodic antennas.

For the 8-element antenna, the feed line (center line) measures 2.87 mm. As illustrated in Figure 7, the impedance matching for 8-element and 10-element log-periodic antennas is relatively degraded compared to the 13-element configuration. However, as previously noted, the 8-element antenna exhibits significantly better matching at the resonance frequency. Consequently, it is logical to compare the measured gains of 8- and 10-element antennas with those of the 13-element model. The graph below (Figure 13) presents the frequency dependence of the gain coefficients for the 13, 10 and 8-element log-periodic antennas across the entire frequency range of 1-3 GHz [15-17].

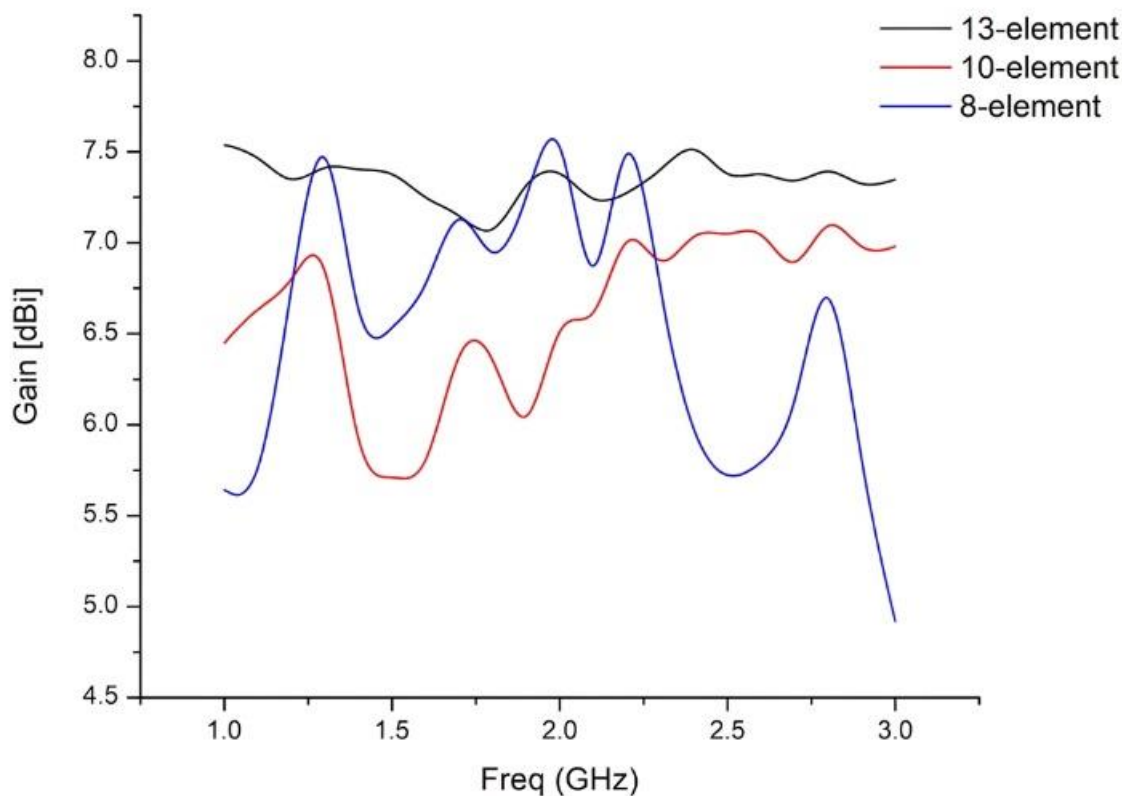


Figure 13.

Frequency dependence of the measured gain coefficients for all three LPDA antennas within the 1-3 GHz range.

Despite the utilization of an FR-4 substrate, a radiation efficiency of 70% was achieved for the 13-element LPDA, which is close to the optimal limit for this low-cost material. The reduction in efficiency observed in the models with fewer elements (8 and 10 elements) is attributed to both increased VSWR and a higher proportion of dielectric losses within the substrate. The efficiency of the 10-element model remains within the range of 55-60%, while the 8-element antenna often approaches 50-52%; however, it can reach approximately 70% at specific resonance frequencies [13, 15].

6. Discussion

The performance evaluation of the designed LPDAs demonstrates a clear relationship between the structural complexity and the electromagnetic stability of the antenna. The following points synthesize our findings in the context of existing literature and theoretical expectations.

6.1. Trade-off Between Element Density and Gain

The 13-element LPDA exhibited the most consistent gain characteristics (7.1-7.6 dBi), aligning with the classical design principles established by Carrel and later refined by Djordjevic et al. [13]. The stability of the gain in the 13-element model is a direct result of a well-defined “active region.” As noted by Vieira [10], when the scaling factor is optimized for a larger number of elements, the transition of the phase center along the antenna’s axis becomes more linear, minimizing the gain ripples observed in

the 8-element configuration. The fluctuations seen in the 8-element model (up to 1.5 dB variation) suggest that, for high-precision communication links, the reduction in element count significantly compromises the frequency-independent nature of the array [8].

6.2. Impact of FR4 Dispersion on VSWR

While the VSWR for all models remained within the acceptable limit of < 2.0 , a noticeable shift in resonant frequencies was observed between the simulated and fabricated prototypes. This phenomenon is frequently discussed in the literature concerning printed antennas on low-cost substrates. According to Gupta et al. [11], the non-uniformity of the dielectric constant (ϵ_r) in the FR4 laminates can lead to a deviation in the electrical length of the dipoles. In our study, the slight upward shift in the measured VSWR minima at 3 GHz suggests that the actual ϵ_r of the substrate was lower than the 4.4 used in the CST model. Furthermore, the loss tangent ($\tan \delta = 0.02$) of FR4 contributes to a reduction in radiation efficiency, which was calculated to be approximately 70% (measured) for the 13-element model, consistent with the finding of Baghel et al. [14].

6.3. Pattern Symmetry and Front-Back Ratio

The radiation patterns obtained in the anechoic chamber validated the high directivity of the 13-element array. A critical observation was the maintenance of a high front-to-back (F/B) ratio across the 1-3 GHz band. As theoretically predicted by Brinca [9], the passive elements outside the active region serve as crucial reflectors and directors. In our 8-element model, the F/B ratio degraded at the upper frequency limit, which indicates that the truncated geometry is insufficient to suppress backward radiation effectively. This validates the necessity of maintaining a minimum number of elements to preserve the directional integrity of the LPDA [12].

6.4. Practical Feasibility and Cost-Efficiency

Despite the inherent dielectric losses associated with FR4, the results confirm that for a wideband spectrum (1-3 GHz), this substrate remains a cost-effective alternative to high-end materials like Rogers. The successful implementation of these antennas for applications such as GSM, GPS, and Wi-Fi proves that geometric optimization can mitigate material limitations [15]. The 13-element design, in particular, offers a robust balance, providing professional-grade performance at a fraction of the cost of traditional wideband antennas.

7. Conclusion

The comprehensive investigation conducted in this study provides a clear roadmap for the design and optimization of printed Log-Periodic Dipole Array antennas within the 1-3 GHz frequency spectrum. Through a systematic comparison of 8, 10, and 13-element configurations, we have successfully characterized the performance trade-offs involved in balancing antenna compactness with electromagnetic stability.

The empirical evidence and simulation data lead to the following key conclusion:

1. **Structural Optimization:** The 13-element LPDA configuration emerged as the superior design, providing a stable realized gain of 7.1-7.6 dBi and excellent VSWR characteristics across the entire bandwidth. This confirms that a higher element density is essential for maintaining the “frequency-independent” property of the array when using lossy substrates.
2. **Substrate Viability:** The study validates the use of FR4 laminate as a cost-effective alternative for wideband applications in the microwave range. While the substrate’s loss tangent slightly reduces overall efficiency compared to high-frequency laminates, the optimized geometry of the 13-element model effectively compensates for these limitations, maintaining an efficiency of approximately 70%.

3. Compactness vs. Performance: It was demonstrated that, while reducing the element count to 8 dipoles significantly minimizes the physical footprint, it introduces undesirable fluctuations in the radiation pattern and gain stability. Therefore, the 8-element version is recommended only for low-power, short-range applications where size is the primary constraint.
4. Practical Application: The successful alignment between CST simulations and anechoic-chamber measurements confirms that the proposed designs are ready for integration into modern communication systems, including GPS, GSM-1800, and 2.4 GHz ISM-band technologies.

Future work will focus on exploring fractal-shaped dipole elements to further reduce the physical dimensions of the LPDA without compromising the element count, as well as investigating active impedance-matching techniques to enhance performance at the lower end of the frequency band. This study serves as a foundational framework for developing affordable, high-performance, wideband antennas for the next generation of wireless communication devices.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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