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Design and Simulation of a Phase-Stable Printed Log-Periodic Biconical Dipole Array

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Abstract: *This paper presents the design and simulation process of a wide-band printed log-periodic biconical dipole array (PLPDA) antenna. The main objective of this antenna is to serve as a feed for a reflector, operating within a frequency range of 0.9 to 5 GHz. The PLPDA design incorporates an iron bar connected to a reflector that measures 95 cm in diameter to achieve this. The simulation of the antenna is performed using the CST Studio suite. Furthermore, the antenna and reflector combination exhibits an efficiency of about 56%. The selection of a biconical dipole for the design of the PLPBDA is based on the need for a minimum size. The biconical dipole design offers a larger bandwidth compared to other options, allowing for a wider range of frequencies to be covered with a smaller number of dipoles. The simulation results demonstrate that the PLPDA, with dimensions of on an RO4003C substrate, achieves a value below -10 dB. By utilizing a biconical dipole instead of a regular LPDA, the antenna achieves a 37.4% reduction in length and an overall width reduction of 72%.*

Keywords: *Printed Log-Periodic Biconical Dipole Array (LPBDA), Reflector, Efficiency*

1. Introduction

From radar tracking to satellite communications, reflector antennas have applications in a great number of fields.[1-2] Reflector antennas have become an essential component of many domains thanks to their versatility, reliability, and performance. These antennas have played important roles in various fields beyond satellite communications and radar tracking, including deep space exploration, radio astronomy, and establishing wireless internet connections. Capabilities to guide and modulate electromagnetic waves have transformed our communication and observation of the surrounding environments. Reflector antennas are an essential component for various fields like space, telecommunication, and scientific exploration.

The most commonly used feeding antennas are horn antennas, log-periodic dipole arrays, and spiral antennas.[3-5] These antennas each have their own unique characteristics that make them suitable for various applications. Horn antennas, known for their directional properties, are often used in microwave applications due to their ability to focus energy in a specific direction. Log-periodic dipole arrays, on the other hand, are favored for their broadband capabilities, making them ideal for wide frequency range communication systems. Spiral antennas, with their compact size and circular polarization features, find their niche in satellite communication and radar systems where space is limited but performance is crucial.

The PLPBDA antenna is a versatile and simple structure that offers several advantages. It provides reasonable gain, a narrow beam, and maintains a constant input impedance over a wide bandwidth. These characteristics make it suitable for a variety of applications, including being used as a feed for reflector antennas, lenses, and signal detection systems. Overall, the PLPBDA antenna's performance and adaptability make it an excellent choice in many scenarios [4][8-9].

Furthermore, an LPDA antenna is considered frequency-independent when the higher frequency is at least ten times greater than the lower frequency, resulting in consistent impedance and radiation characteristics across the frequency range. The size of the LPDA antenna is primarily determined by its lower operating frequency, resulting in a longer dipole. However, for wide operation frequency bands starting at 900 MHz, the LPDA length becomes significantly large. To address this limitation, a new alternative known as the printed log-periodic biconical dipole array (PLPBDA) antenna has emerged. The PLPBDA antenna utilizes printed circuit board (PCB) technology, offering several advantages such as affordability, a low profile, compact size, and easy fabrication [4][9].

In our research, we present a wide-band Log-Periodic Biconical Dipole Array (PLPBDA) inspired by the design outlined in "Design a Compact Printed Log-Periodic Biconical Dipole Array Antenna for EMC Measurements" published in Electronics[9]. This antenna is engineered to operate efficiently in the S and L bands, covering an extensive frequency range from 0.9 GHz to 5 GHz. The PLPBDA exhibits remarkable performance, consistently maintaining a stable radiation pattern across the entire operational bandwidth. To ensure the robustness of our design, we conducted comprehensive simulations using the CST Studio Suite 2023. Our simulation results encompass detailed measurements and radiation patterns at various frequencies within the specified band. The findings from these simulations underscore the antenna's effectiveness and reliability in wide-band operations. The PLPBDA demonstrates reasonable gain and a narrow beam, maintaining a constant input impedance over a wide bandwidth. This makes it an excellent choice as a feed for reflector antennas, offering high efficiency and stable performance. Furthermore, the compact design and printed structure of the antenna offer significant advantages in terms of ease of fabrication and integration into modern electronic systems. Our work highlights the potential for the PLPBDA to serve as a highly efficient and practical solution in wide-band applications, promising enhanced performance and stability.

2. Antenna Design

To design a log-periodic dipole array (LPDA), a specific formula can be used [6][9]. By employing this approach, a compact LPDA with dimensions of $50 \times 25 \times 5\ cm^3$ and 24 dipoles can be achieved, as depicted in Figure 1. However, when using this as a feed reflector, there are challenges in attaining optimal efficiency. To overcome this issue, a biconical dipole can be utilized instead, providing greater bandwidth with fewer dipole elements. Consequently, this results in a smaller overall structure and improved efficiency. The log-periodic biconical dipole array antenna (PLPBDA) has dimensions of $18.7 \times 18.35 \times 0.16\ cm^3$ and features 16 biconical dipoles. In comparison, a biconical dipole instead of the traditional dipole, the antenna attains impressive improvements. Firstly, its length is remarkably reduced by 37.4%. Additionally, the overall width of the antenna experiences a substantial reduction of 72%. These advancements in design not only enhance the antenna's efficiency but also contribute to a more compact and lower loss.

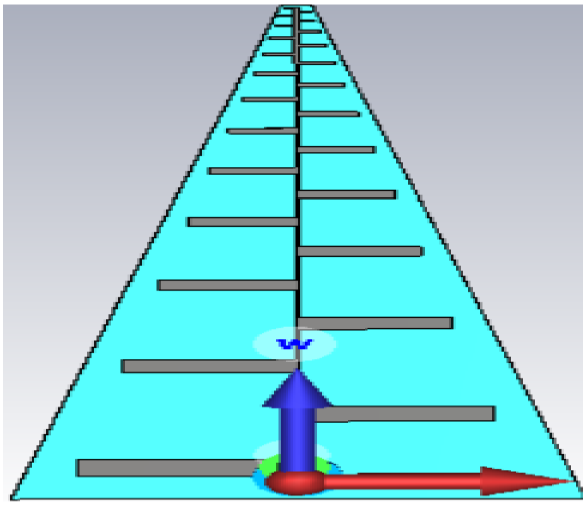


Fig1. *Printed Log-Periodic Dipole Array (LPDA)*

The printed log-periodic biconical dipole antenna is a unique and versatile design that incorporates multiple dipoles. Each dipole within the antenna is specifically designed to resonate at a particular wavelength, determined by its length. Interestingly, dipoles with lengths exceeding the wavelengths they resonate at serve as reflectors, while those with shorter lengths act as directive dipoles. This distinctive behavior allows the log-periodic biconical dipole antenna to adapt to various requirements. To determine the dimensions of the antenna, we employ a set of ten equations [6] [10]. These equations enable us to calculate the optimal lengths and spacing between the dipoles, ensuring efficient performance. By optimizing the antenna's dimensions, we aim to achieve desirable characteristics such as a good S_{11} (return loss) and gain. Through this optimization process, we identify the most suitable dimensions for the log-periodic biconical dipole antenna. These dimensions offer a balanced combination of S_{11} and gain, resulting in enhanced overall performance.

$$N = 1 + \frac{\log B_s}{\log\frac{1}{\tau}} \tag{1}$$

Bs and Bar are crucial factors in determining the bandwidth of the structure and active region, respectively.

$$B_s = B \cdot B_{ar} = \frac{f_{upper}}{f_{lower}} \times B_{ar} \tag{2}$$

$$B_{ar} = 1.1 + 7.7(1-\tau)^2 \frac{4\sigma}{1-\tau} \tag{3}$$

$$L_1 = \frac{1}{2} \times \frac{c}{f_{lower}} \tag{4}$$

$$R_1 - R_2 = \frac{L_1 - L_2}{2} \times \frac{4\sigma}{1-\tau} \tag{5}$$

$$Z_0 = \frac{377}{\pi}\left(\ln\left(\frac{L_n}{a_n}\right) - 2.25\right) \tag{6}$$

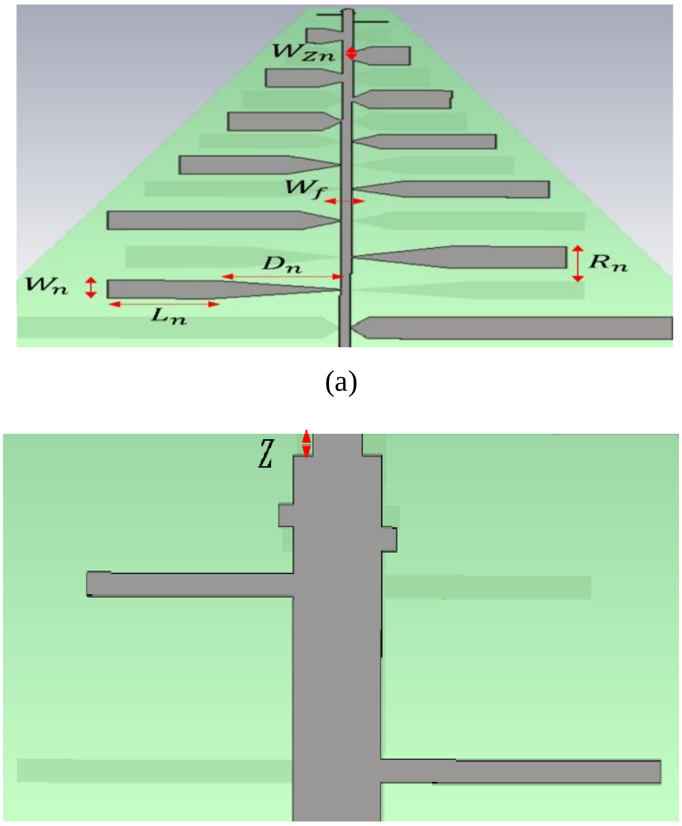
$$W_n = \pi \times a_n \tag{7}$$

$$L_n = \tau \times L_{n-1} \tag{8}$$

$$R_n = \tau \times R_{n-1} \tag{9}$$

$$W_n = \tau \times w_{n-1} \tag{10}$$

Based on the numerical analysis presented in the range of (1)-(10) above, we have successfully optimized the antenna design depicted in Figure 2. The corresponding dimensions of this optimized antenna are provided in Table 1.



(a)

(b)

Fig2. *Printed Log-Periodic biconical Dipole Array (PLPBDA) (a) Front view of the antenna. (b) Close-up top view of the antenna.*

TableI. *Specification of LPDA*

Para-meters	Value(mm)	Para-meters	Value(mm)	Para-m-eters	Value(mm)	Para-m-eters	Value(mm)
L_1	90	W_5	9	D_9	5	W_{Z1}	0.5
L_2	65	W_6	10	D_{10}	6.25	W_{Z2}	0.5
L_3	60	W_7	8	D_{11}	5	W_{Z3}	0.5
L_4	65	W_8	10	D_{12}	5	W_{Z4}	0.5
L_5	55	W_9	10	R_1	20	W_{Z5}	0.5
L_6	45	W_{10}	10	R_2	19	W_{Z6}	0.5
L_7	40	W_{11}	11	R_3	19	W_{Z7}	0.5
L_8	31.8	W_{12}	8	R_4	17	W_{Z8}	0.5
L_9	27.5	W_{13}	0.5	R_5	13.7	W_{Z9}	2
L_{10}	21.2	W_{14}	0.5	R_6	12	W_{Z10}	4.5
L_{11}	16	W_{15}	0.5	R_7	12	W_{Z11}	4.5
L_{12}	10	W_{16}	0.5	R_8	12	W_{Z12}	4.5
L_{13}	9.5	D_1	5	R_9	12	W_{Z13}	0.5
L_{14}	7	D_2	35	R_{10}	12	W_{Z14}	0.5
L_{15}	0.5	D_3	27.5	R_{11}	10	W_{Z15}	0.5
L_{16}	0.5	D_4	11.25	R_{12}	4	W_{Z16}	0.5
W_1	12	D_5	15	R_{13}	4	Z	0.5
W_2	10	D_6	15	R_{14}	1		
W_3	12	D_7	8	R_{15}	0.5		
W_4	10	D_8	5.25	W_f	3		

In the design of a biconical array antenna, it is proposed to use 12 trapezoidal shapes instead of the conventional dipole array. Additionally, incorporating 4 classical dipole elements will ensure consistent and favorable gain. The overall dimensions of the Log Periodic Biconical Dipole Array (PLPBDA) with 16 dipoles measure 18.7 × 18.35 × 0.16 cm. These dimensions, as outlined in Table 1, are crucial for the accurate development of the PLPBDA using CST Studio Suite. To safeguard the PLPBDA, it is recommended to employ a Teflon radome with an epsilon value of 2.1. This radome will provide protection and maintain the optimal performance of the antenna. For the connection between the PLPBDA and a 95 cm in diameter reflector, the measurements entail a length of 34.62 cm, a width of 2 cm, and a height of 1 cm. These dimensions are vital for establishing a secure and efficient connection between the PLPBDA and the reflector. To visualize the configuration, Figures 3 and 4 offer graphical representations, illustrating the arrangement of the reflector, iron bar, and the PLPBDA with the radome. These visuals provide a clearer understanding of how the components come together in the overall setup.

To utilize PLPBDA as a feed for a 95 cm in diameter reflector with an f/d ratio of 0.375, it is crucial to establish the phase center of the log-periodic dipole array (PLPBDA). By employing optimization techniques, we can effectively incorporate fourteen dipoles within the confines of the 35.625 cm reflector.

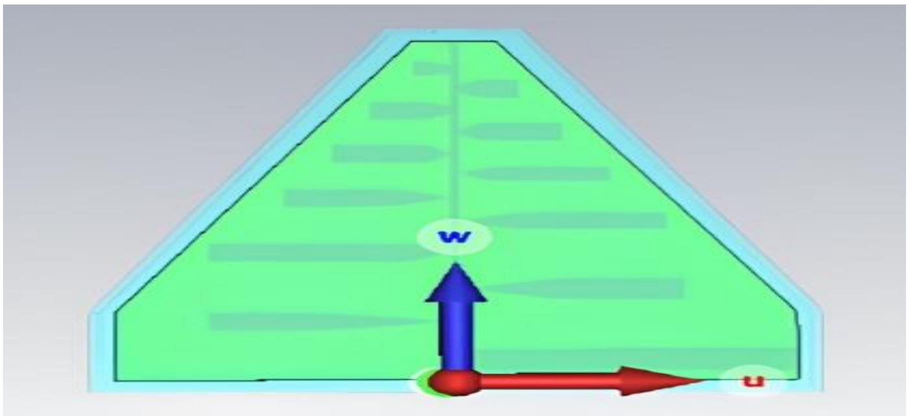


Fig3. *Printed Log-Periodic Biconical Dipole Array with radome.*

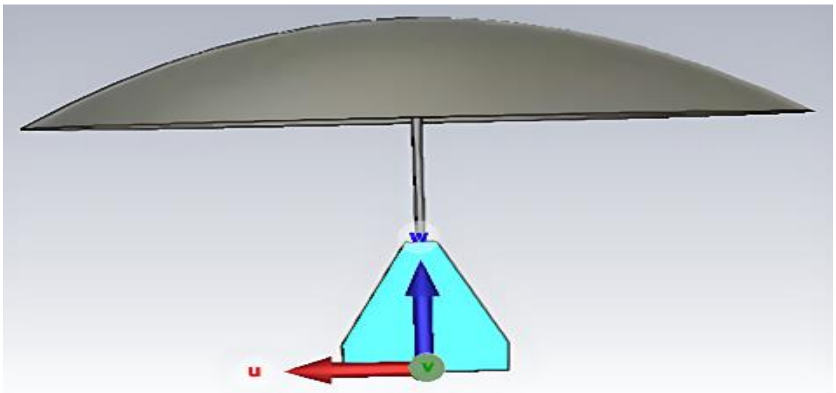


Fig4. *LPDA with reflector and iron bar.*

3. Simulation and Measurement Results

After completing the design process for the PLPBDA antenna, which included integrating a radome, iron bar, and reflector in the CST studio site, the next steps were simulation and measurement. These stages are crucial for evaluating the performance and characteristics of the antenna.

3.1. Reflection Coefficient

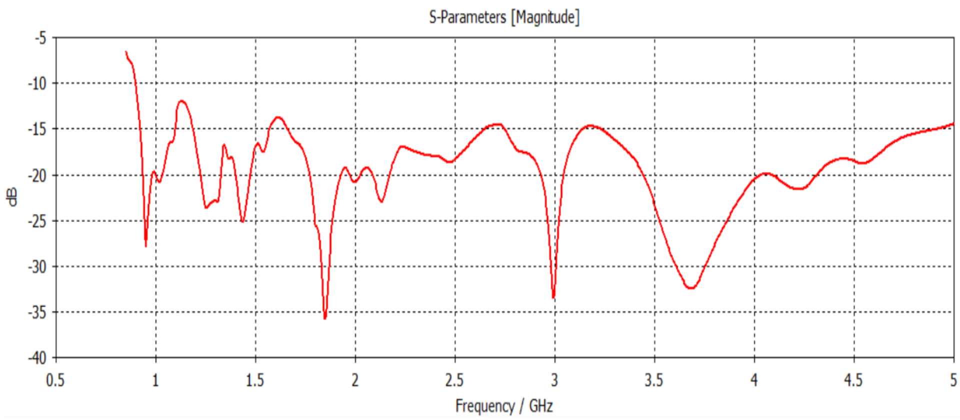


Fig5. *Reflection coefficient of LPDA on CST Studio Suite2023.*

In Figure 5, the reflection coefficient of the Printed Log-Periodic Biconical Dipole Array (PLPBDA) simulated using CST Studio Suite 2023 is depicted. Throughout the frequency range of 0.9 to 5 GHz, the S_{11} of the antenna consistently remains below -10 dB, indicating excellent impedance matching. Additionally, the voltage standing wave ratio (VSWR) remains below 2, further confirming the antenna's efficient performance within its bandwidth. Speaking of bandwidth, the PLPBDA has a measured bandwidth of 4.1 GHz, showcasing its ability to operate effectively across a wide range of frequencies.

4. Radiation Pattern and Efficiency

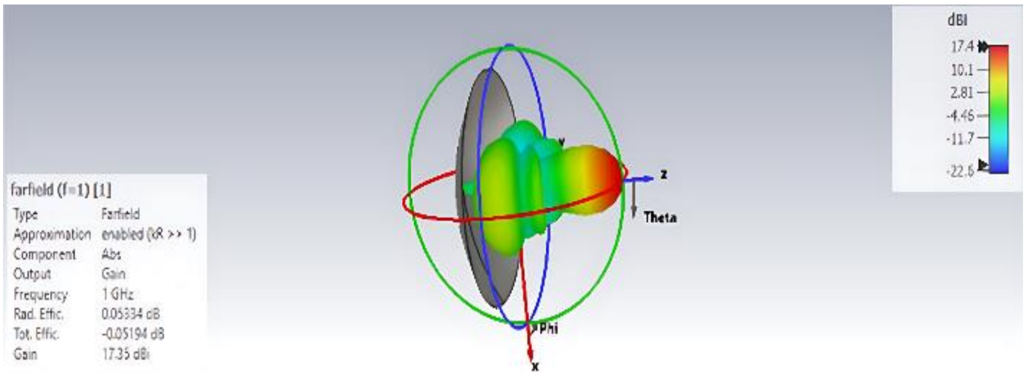


Fig6. *Radiation pattern result on CST Studio 2023 on frequency 1 GHz.*

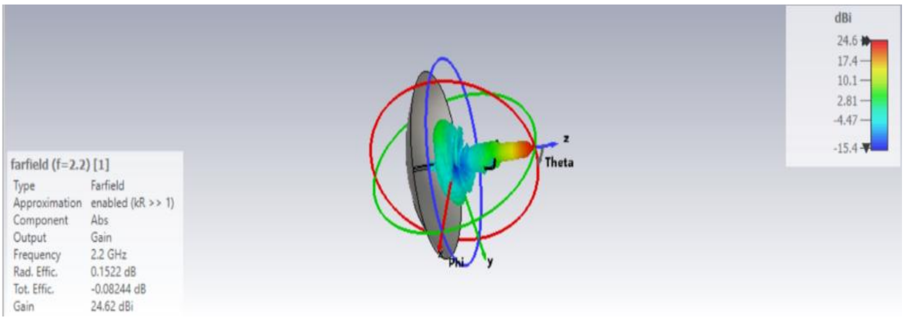


Fig7. *Radiation pattern result on CST Studio 2023 on frequency 2.2 GHz.*

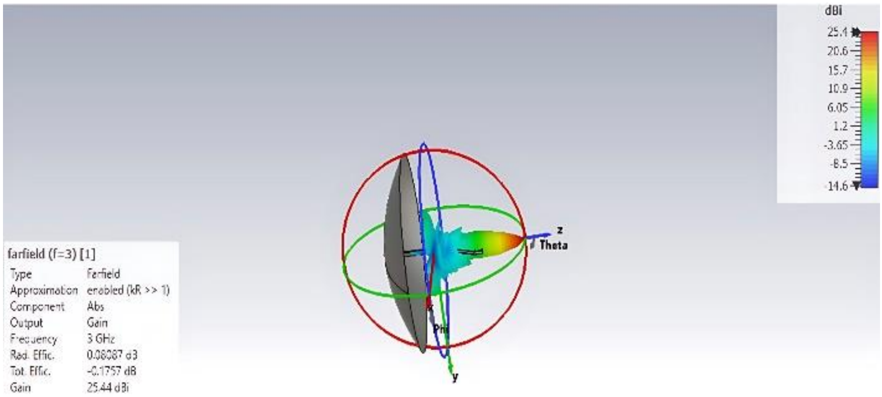


Fig8. *Radiation pattern result on CST Studio 2023 on frequency 3 GHz.*

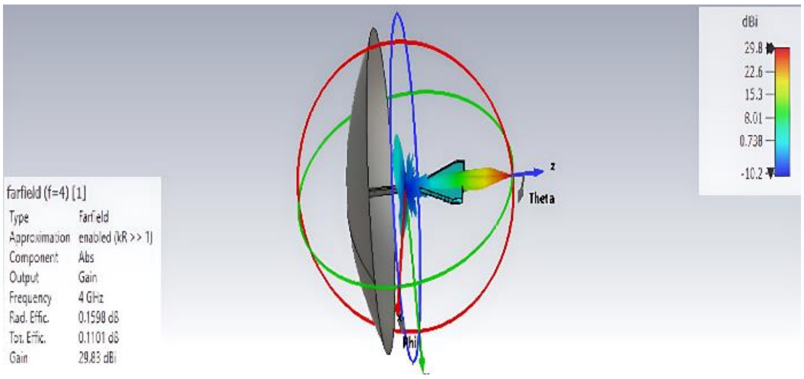


Fig9. *Radiation pattern result on CST Studio 2023 on frequency 4 GHz.*

Figures 6 to 9 depict the radiation pattern of the PLPBDA (Log Periodic Biconical Dipole Array) antenna in front of a reflector. The antenna exhibits a gain of 17.4 dB, 24.6 dB, 25.4 dB, and 29.8 dB at frequencies of 1 GHz, 2.2 GHz, 3 GHz, and 4 GHz respectively. It is evident that the antenna achieves significant gain across this frequency range, indicating its effectiveness.

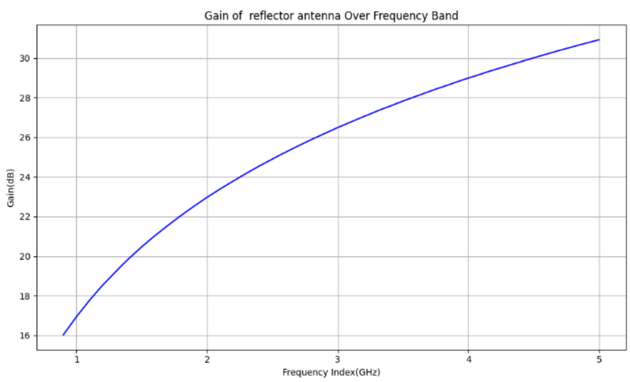


Fig10. *Antenna Gain over frequency band.*

Figure 10 depicts the antenna gain across different frequencies. It clearly shows that the gain of the antenna increases as the frequency rises. Specifically, at a frequency of 0.9, the antenna exhibits a gain of 16.03 dB, while at a frequency of 5, the gain increases significantly to 30.92 dB.

The efficiency of a Printed Log-Periodic Biconical Dipole Array (PLPBDA) positioned in front of a reflector is an important factor to consider. When an antenna is placed in front of a reflector, it interacts with the reflected waves to enhance its performance. The efficiency of this arrangement refers to how effectively the antenna captures and radiates electromagnetic energy. In order to achieve optimal efficiency, it is essential to consider various factors. One of the key factors is the design of the antenna and reflector, which includes carefully determining their size and shape to enhance their interaction. Additionally, the spacing between the antenna and reflector, commonly referred to as the distance, is of utmost importance in determining efficiency. To address these considerations, we have successfully developed an antenna with exceptional performance and have also optimized the distance between the LPDA and reflector in section two.

To evaluate the efficiency of the Printed Log-Periodic Biconical Dipole Array (PLPBDA) in conjunction with a 95 cm in diameter reflector, we can employ equations 11, 12, and 13. Equations 11 and 12 allow us to determine the maximum directivity across the frequency band; also, equation 13 allows us to determine the efficiency of the antenna. By utilizing these equations, we can establish a comprehensive understanding of the antenna's performance in terms of its ability to focus and radiate electromagnetic waves efficiently.

$$D_{\max(dB)} = 10 \times log_{10}{}^{\frac{4\times\pi\times A_{aperture}}{\lambda^2}} \tag{11}$$

Where d is the diameter of the reflector.

$$A_{aperture} = \pi \times \left(\frac{d}{2}\right)^2 \tag{12}$$

$$Efficiency(\%) = \left(\frac{Directivitt(simulation)}{Max\ Theorical\ Directivity}\right) \times 100 \tag{13}$$

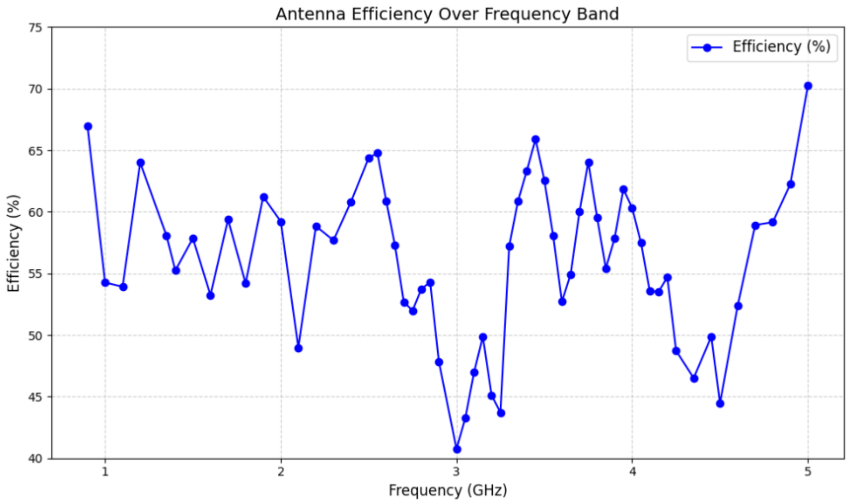


Fig11. *Efficiency of Antenna over frequency band.*

In Figure 11, the efficiency of the antenna is depicted, showcasing its rapid changes across different frequency bands. Notably, the antenna exhibits a minimum efficiency of 40.94 at 3 GHz and a maximum efficiency of 71 at 5 GHz; the antenna maintains an average efficiency of 56% throughout the frequency spectrum. This significant range of efficiency highlights the exceptional performance of the PLPBDA, iron bar, and reflector components. When an antenna operates with 56% efficiency in the presence of a reflector, it indicates that only half of the power is efficiently radiated, while the other half is lost.

5. Conclusion

The ultra-wideband PLPBDA antenna is specifically designed to be used as a reflector feed, providing optimal functionality. It has a reflection coefficient of less than -10 dB across the frequency range of 0.9-5 GHz, ensuring exceptional performance. With a high gain maintained throughout the entire frequency band, the antenna enhances signal reception effectively. Additionally, it operates with remarkable efficiency, boasting an efficiency of approximately 56% across the entire frequency range. This ensures maximum utilization of transmitted or received signals. The PLPBDA antenna has dimensions of $18.7 \times 18 \times 0.16\ cm^3$ and features 16 biconical dipoles. By implementing a biconical dipole instead of the conventional dipole, the antenna effectively reduces its length by 37.4% and achieves an impressive 72% reduction in overall width.

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