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A novel design of high performance multilayered cylindrical dielectric lens antenna using 3D printing technology

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Abstract
In this work, design and realization of high performance, low-cost X-band multilayered cylindrical dielectric lens antenna (MLCDLA) is presented using 3D printing technology. Firstly, MLCDLA is designed and simulated in the complete 3D CST microwave studio (MWS) within the X- band as consisting of six layers and being fed through a conventional rectangular waveguide (WR90). These layers are in the form of cylindrical discs having different radii, thicknesses and made of a cheap polylactic acid material. These layers have also varying dielectric constant from 1.2 to 2.7 that are compatible for fused deposition modeling (FDM) based 3D-printing process. Secondly, a prototype of MLCDLA is produced by using a FDM based 3D-printer. 3D printed dielectric lens antenna is measured and a good return loss of almost more than 10 dB within the X-band with a high gain of 16-18 dBi are achieved as compared with the counterpart alternative designs. Thus, it can be concluded that the proposed novel design and prototyping method not only achieves the high radiation performance characteristics along X-band but also is a fast, low-cost, and effective method for prototyping dielectric lens structures for the microwave applications.

KEYWORDS
3D printer, broadband, high gain, lens antenna, nonuniform lens

1 | INTRODUCTION

High gain antennas are one of the vital components in the versatile wireless systems spanning from radio astronomy and radar to satellite communication. One conventional technique for high gain antenna design is the antenna array design. However, this design method has a major disadvantage of transmission loss due to the increase in the number of feeding elements or complexity of feeding network with the result of degradation in the total antenna efficiency in addition to the requirement of precise geometric positioning of radiating elements for low mutual intercoupling. Another design technique of the high gain antennas is to excite the multimode resonance field patterns of a dielectric lens fed by a primary source in the form of single feed or array termed as dielectric resonator antennas (DRA) which are widely used in millimeter wave applications including automotive radar systems,[1,2] satellite transmission components,[3] and indoor communication networks.[4] These antenna types have the advantages of wide bandwidth, good radiation stability over the operation frequency band with a high gain. However, DRA designs suffer the disadvantages of being bulky with complex geometrical shapes that are either infeasible or impossible to be prototyped via traditional manufacturing methods. Another solution for high gain antenna designs is dielectric lens antennas. Dielectric lenses are conventionally used in focusing to enhance directivity of the primary radiating source. Similar to the glass lenses frequently used in the optical field,[5] dielectric lenses are used in the microwave antenna designs to improve antenna gain characteristics since they are capable of converting incoming quasi-spherical wave into almost plane wave. In literature, there are many different types of microwave lens implementations for the antenna gain improvements.[5-8]

Components with three-dimensional (3D) geometrical structure have gained significant interest in the recent years due to the final innovations in 3D printing technology. Nowadays, 3D printers are extensively used in many applications ranging from medical, industrial art, jewelry, and automotive industry to electronic circuits. Due to the layer-by-layer construction ability, 3D printers have the advantage of prototyping of complex designs that are extremely difficult and expensive to prototype with the conventional fabrication methods. Especially in the field of microwave circuit designs, 3D printers have received great attention due to the precise, fast, and low cost manufacturing capabilities for the prototyping of versatile RF circuits and components.

Although there are many types of 3D printing process such as stereolithography, digital light processing, laminated object manufacturing, fused deposition modeling (FDM), selective laser sintering, selective laser melting, and digital beam melting, FDM and direct metal laser sintering (DMLS) have been used extensively in prototyping of microwave component. In References 9-11, applications of DMLS and printing for manufacturing of waveguides, waveguide-based passive microwave components, antennas, and antenna arrays were studied. In References 12 and 13, application of metallic printers for prototyping of horn antenna designs was studied. Although metallic printing is an effective prototyping method, FDM printing has also been used for 3D printing of microwave stages, such as reflectarray antennas,[14,15] flexible antennas,[16,17] multilayered dielectric loaded antenna,[18] quasi-Yagi antenna,[19] microstrip patch antenna,[20] X-band horn antennas,[21] and realization of dielectric sheets for gain improvement of ultra-wideband horn antennas.[22]

In this article, a novel 3D-printed nonuniform, broadband, and high gain dielectric lens antenna design is presented. The proposed antenna is designed with a six-layered lens plates fed by a rectangular waveguide. The dielectric lenses in the form of flat plates are made of a cheap polylactic acid (PLA) material with dielectric property varying from 1.2 to 2.7. The base PLA material is also compatible to be used in FDM based 3D-printing process. The high gain feature is achieved by installing the layers of dielectric lenses starting from the low valued dielectric material to the high valued material to have a tapered matching effect. The numerical computation results of the proposed antenna design are verified by the experimental measurement results of the 3D printed design prototype. Furthermore, the experimental results are compared with the counterpart antenna designs in the literature. The simulation and experiment results prove the advantage of the proposed simple non-uniform multilayer dielectric lens design as compared to the counterpart designs using the unique ability of 3D printing technology to realize nonuniform layers of lens structure.

2 | DESIGN OF MULTILAYERED CYLINDRICAL DIELECTRIC LENS

In this section, the design of the proposed multilayered cylindrical dielectric lens is presented. The proposed antenna design is based on six-layered lens plates fed through a rectangular waveguide. The geometric parameters of each layer are indicated in Figure 1. The technological advance of prototyping abilities of 3D printers facilitates to use versatile base materials with different dielectric constants to be manufactured by only changing the infill rate of deposited material (the volume fraction of the thermoplastic to the total volume).[20,23] Thus, in the proposed antenna design, not only

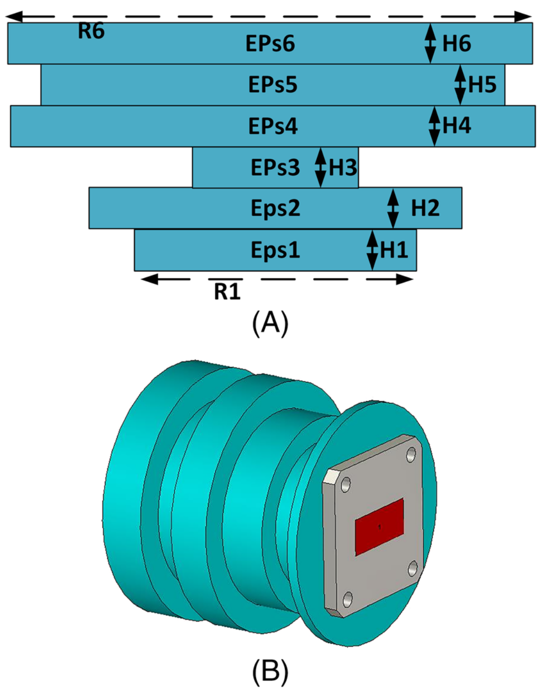

FIGURE 1 Schematic and geometrical structure of the proposed MLCDLA

TABLE 1 Parameter values of the fabricated lens case 1

Eps1	1.2	H1	3	R1	33.4
Eps2	1.87	H2	12.6	R2	20.8
Eps3	2.15	H3	13	R3	27.2
Eps4	2.27	H4	11.4	R4	34.8
Eps5	1.9	H5	10	R5	26.8
Eps6	2.5	H6	12.6	R6	35

Note: H1-H6 and R1-R6 values are given in millimeter.

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TABLE 2 Parameter values for parametric analysis

Case 2	Eps1	Eps2	Eps3	Eps4	Eps5	Eps6
	Same with case 1					
	H1	H2	H3	H4	H5	H6
	10					
	R1	R2	R3	R4	R5	R6
	Same with case 1					
Case 3	Eps1	Eps2	Eps3	Eps4	Eps5	Eps6
	2.5					
	H1	H2	H3	H4	H5	H6
	Same with case 1					
	R1	R2	R3	R4	R5	R6
	Same with case 1					
Case 4	Eps1	Eps2	Eps3	Eps4	Eps5	Eps6
	Same with case 1					
	H1	H2	H3	H4	H5	H6
	Same with case 1					
	R1	R2	R3	R4	R5	R6
	35					
Case 5	Eps1	Eps2	Eps3	Eps4	Eps5	Eps6
	1	1.25	1.5	1.75	2	2.5
	H1	H2	H3	H4	H5	H6
	10					
	R1	R2	R3	R4	R5	R6
	35					
Case 6	Eps1	Eps2	Eps3	Eps4	Eps5	Eps6
	Same with case 1					
	H1	H2	H3	H4	H5	H6
	Same with case 1					
	R1	R2	R3	R4	R5	R6
	35	32	29	26	23	20
Case 7	Eps1	Eps2	Eps3	Eps4	Eps5	Eps6
	2.5	2	1.75	1.5	1.25	1
	H1	H2	H3	H4	H5	H6
	10					
	R1	R2	R3	R4	R5	R6
	35					

Note: H1-H6 and R1-R6 values are given in millimeter.

each layer of the lens structure has different height and radius but also dielectric constant values are taken as a design variable for the dielectric lens design. In Reference 20 Equation 1 is presented as a simple expression that calculates the dielectric constant value of a material with respect to the infill rate of the material, based on measured results given in Reference 23, where the variation of dielectric

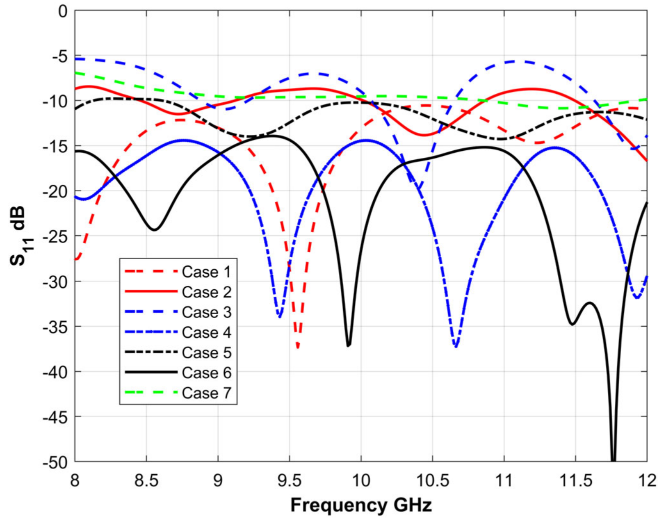

FIGURE 2 Simulated S_{11} analysis of different cases

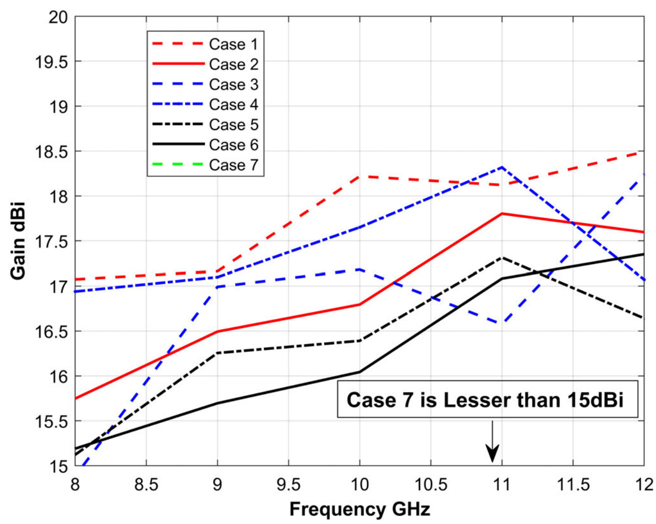

FIGURE 3 Simulated gain analysis of different cases

constant with respect to the infill rate (defined in percent within the limits of 15%-100%) of material, x has been expressed.[20] By using this equation it is possible to design layers with a variant dielectric constant from 1.2 to 2.7:

$$\varepsilon_r = -1.3x10^{-6}x^3 + 0.0374x + \frac{6.42}{x} + 0.217 \qquad (1)$$

The flat discs of dielectric lenses are fabricated with a cheap PLA material of dielectric properties varying from 1.2 to 2.7 by a compatible FDM based 3D-printing process subject to Equation (1). The proposed MLCDLA model shown in Figure 1 consisting of six-layers of cylindrical discs with variable layer height, layer radius, and layer dielectric constants from 1.2 to 2.7. All of these 18 variables indicated in Table 1 are determined via trial and error alongside of using trust region framework (TRF) optimization method embedded in CST provided with the goals of: (a) S_{11} characteristic of less than −11 dB, (b) maximum gain characteristic of more than 16 dBi, over the operation band of 8-12 GHz. Then, finally the determined optimal dielectric constant values in Table 1 are realized from the reverse of Equation 1 adjusting the infill rate of the material to obtain the requested dielectric constant. The computed results of S_{11} and gain parametric analysis are given for seven different cases in Table 2, Figures 2 and 3, respectively. Furthermore, the radiation patterns and E-field distribution of case 1 at 8, 10, and 12 GHz are presented in Figures 4 and 5.

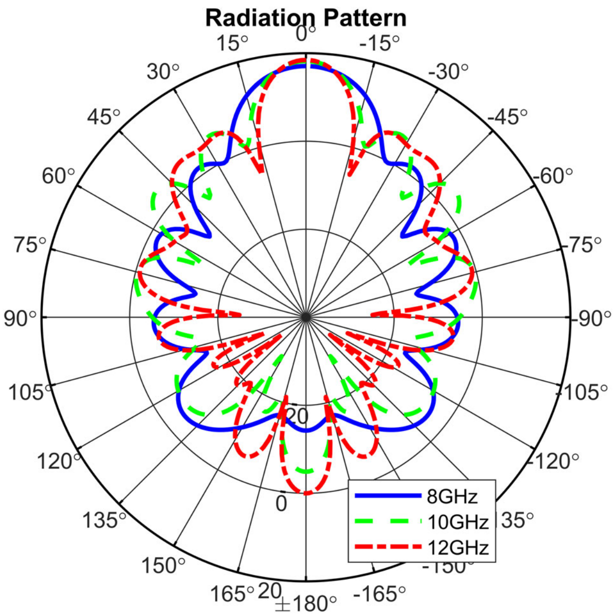

FIGURE 4 Simulated radiation patterns of case 1

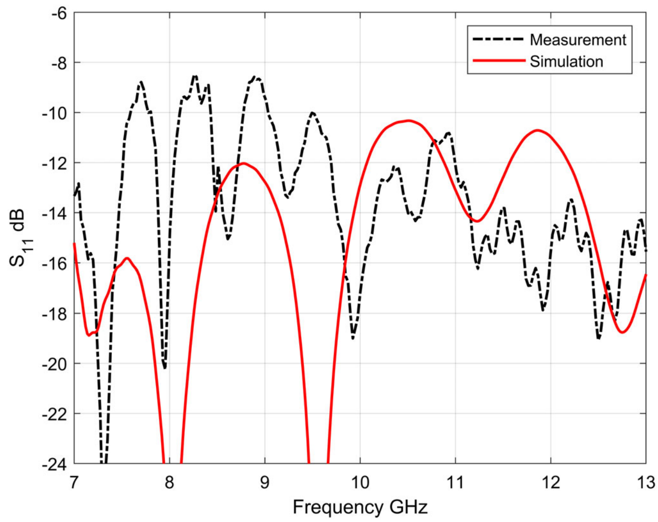

FIGURE 7 Simulated and measured S_{11}

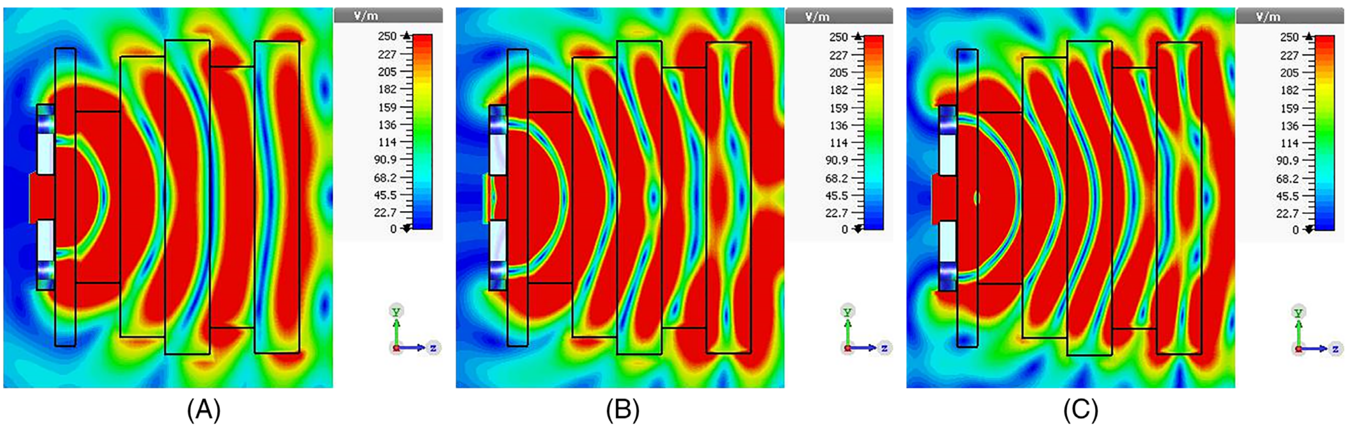

FIGURE 5 Simulated E-field distribution at A, 8 GHz, B, 10 GHz, C, 12 GHz

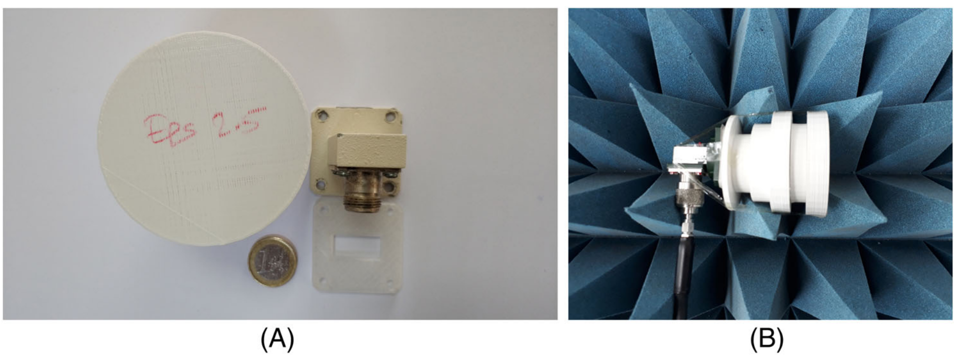

FIGURE 6 Fabricated MLCDLA model

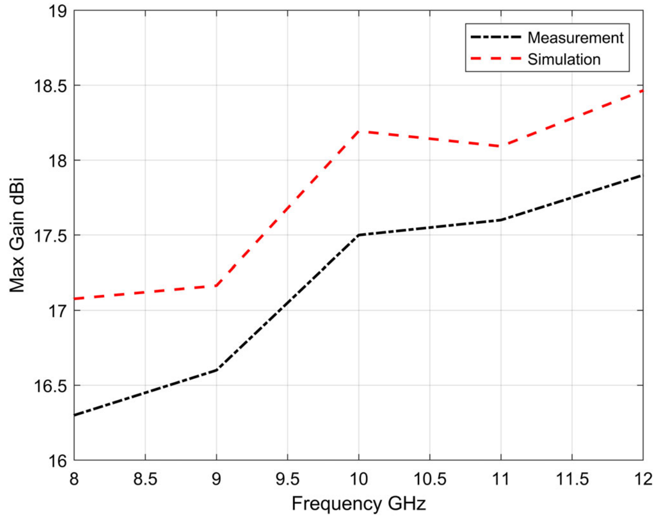

FIGURE 8 Maximum gain over the operation band

3 | 3D PRINTING FABRICATION AND EXPERIMENTAL RESULTS OF MLCDLA

In this section, a prototype of the proposed MLCDLA using 3D printing technology is presented. In Figure 6, the 3D printed MLCDLA and measurement setup are shown. For the RF performance measurement of the proposed 3D printed MLCDLA, a vector network analyzer with the measurement frequency range between 9 KHz and 13.5GHz Rohde–Schwarz RS Zvl13, and "LB8180, 0.8-18 GHz broadband horn antenna"[24] are used.

In Figures 7–9 and Table 3, the measured and simulated results of return loss and radiation pattern of the proposed MLCDLA are given. The computed and measured S_{11} of the MLCDLA are presented in Figure 7. The fundamental reasons

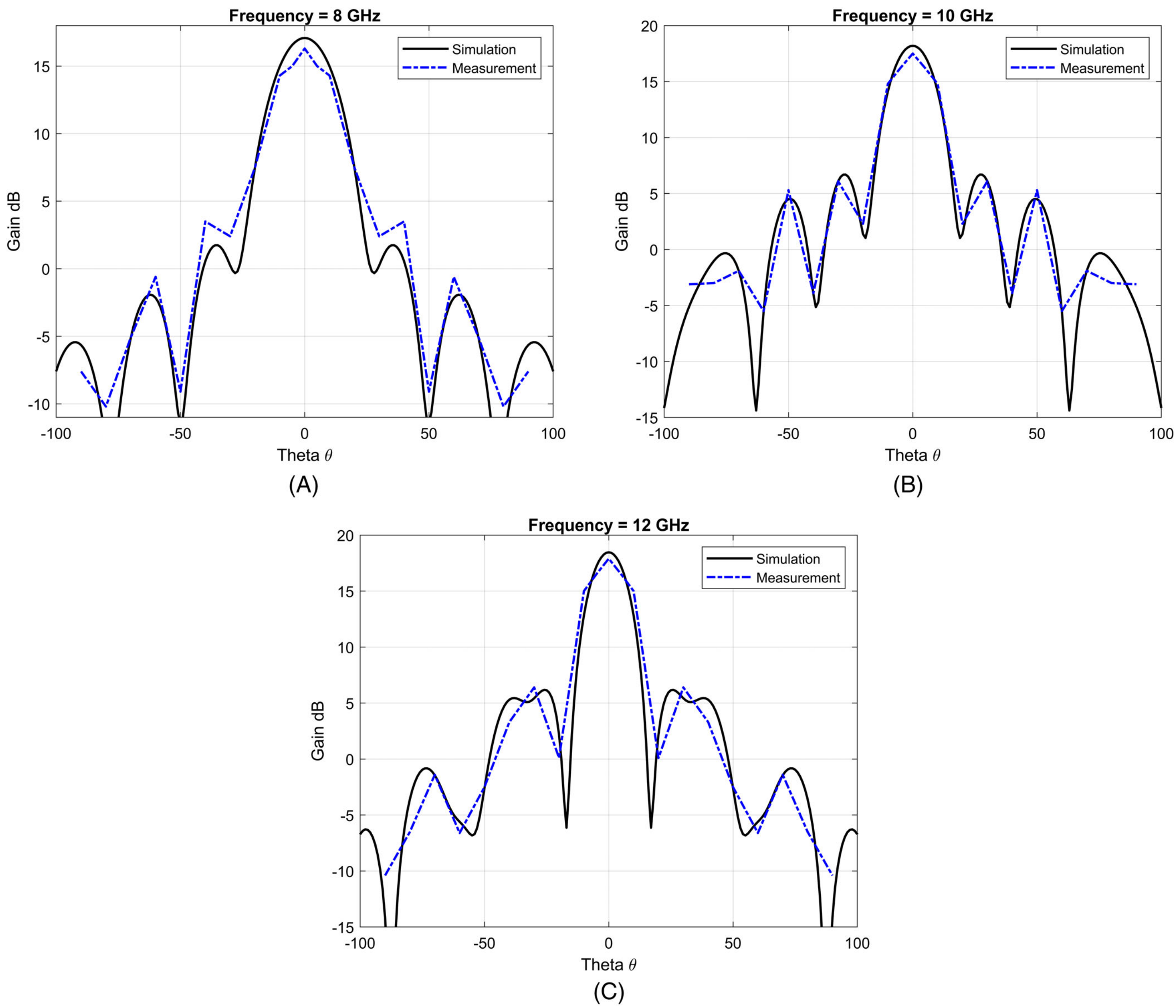

FIGURE 9 Measured radiation patterns of MLCDLA for θ=90° at A, 8 GHz, B, 10 GHz, C, 12 GHz

TABLE 3 Simulated and measured radiation characteristics of the proposed MLCDLA

	S_{11} (dB)		Realized gain (dBi)		Side lobe level (dB)	
f (GHz)	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.
8	<−25	−20.2	17.1	16.3	−15.3	−12.8
9	<−10	−9.8	17.2	16.6	−14.3	−14.8
10	<−10	−17.4	18.2	17.5	−11.5	−11.4
11	<−10	−12.3	18.1	17.6	−11.5	−11.2
12	<−10	−14.8	18.5	18.4	−12.3	−12.1

TABLE 4 Comparison of gain (dBi) enhancements of the typical horn modules in the similar bandwidth

		Gain (dBi) over operation band (GHz)				
	Dielectric size (mm)	8	9	10	11	12
Here	35 × 35 × 62.6	16.3	16.6	17.5	17.6	18.4
[18]	30 × 30 × 52.5	11.2	11.3	14	13.8	12.6
[25]	279 × 244 × 159	16	18	14.8	17	15
[26]	85.1 × 30.8 × 15.9	8.5	9	9	9	10
[27]	90.7 × 210 × 210	…	…	17	…	…
[28]	87.4 × 59.3 × 80	14	15.5	16.5	15	17
[29]	74 × 81.5 × 60	10.7	11.3	8.2	10.2	9.8

of the discrepancy between the simulation and measurement results can be the inherent material based fabrication tolerances, uncertainty in the dielectric constants of the incorporated cylindrical flat layers, calibration errors and RF cabling imposed multi resonance effects. The measured maximum gain and radiation pattern over the operation frequency band are denoted in Figures 8 and 9. As it can be deduced from the figures, the measured and simulated results are in quite good agreement with the designed results of the proposed multilayer dielectric lens structure achieving minimum level of the measured gain as 16.3 dBi over the whole operation band. Thus, the proposed method using 3D printing technology for the design and fabrication of MLCDLA is an efficient solution for the realization of dielectric loaded antennas.

Furthermore, in Table 4, an RF performance comparison of the proposed MLCDLA antenna with the counterpart antennas in the literature operating within the similar operation band is shown. As concluded from the table, the proposed design is significantly better in comparison to the counterpart alternative designs in terms of both size and radiation characteristics.

4 | CONCLUSION

In this article, a high performance multilayered cylindrical dielectric lens antenna is designed with the utilization of 3D printing technology for fast, accurate, and low-cost complex prototyping. The experimental results point out 3D printed antenna to have good reflection parameter characteristics of almost less than −10 dB within the operation frequency range of 8-12 GHz with a good gain of 16-18 dBi. The measured and simulated results are in good agreement, which suggests the prototyped antenna to be suitable for X-band communication applications. Furthermore, an RF performance comparison of the proposed MLCDLA with the counterpart designs operating in similar operation band is also made to prove the current design to be a better alternative to the fabricated designs in terms of both size and radiation characteristics. It can be concluded that the proposed 3D printing method is not only a good fabrication solution to achieve the targeted performance characteristics but also a fast, low-cost, and effective method for prototyping the dielectric lens structures for the microwave applications.

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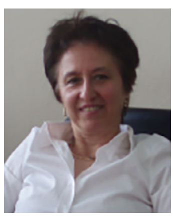

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