Gain Enhancement of a Traditional Horn Antenna using 3D Printed Square-Shaped Multi-layer Dielectric Lens for X-band Applications

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Abstract **─** In this work, gain of a traditional horn antenna is enhanced up to 2.9 dB over X-band using 3D printed square-shaped multi-layer lens. For this purpose, firstly the multi-layer lenses are designed using Invasive Weed Optimization (IWO) and simulated in 3-D CST Microwave Studio (MWS) environment as consisting of square-shaped five layers with variable dielectric constants and heights. Thus, optimum values of the dielectric constants and heights are resulted limiting from 1.15 to 2.1 and 9.2 mm to 10 mm, respectively compatible for Fused Deposition Modeling (FDM) based 3D-printing process. Finally, the optimum lens is realized by 3D printer via FDM evaluating infill rate of cheap Polylactic Acid (PLA) material for each layer. The simulated and measured performance of the multi-layer dielectric structures are hand to hand. The horn antenna equipped by our proposed dielectric lens achieves gain enhancement of the traditional antenna up to 2.9 dB over the operation band. Furthermore, the proposed design is compared with the counterpart designs in literature and based on the comparison results it can be said that the proposed design achieves the better performance in the smaller in size as equipped a traditional X-band horn antenna.

Index Terms **─** 3D printer, dielectric lens, fused deposition modeling, gain enhancement.

I. INTRODUCTION

The X-band is the designation for a band of frequencies. In radar engineering, the frequency range is specified by the Institute of Electrical and Electronics Engineers (IEEE) at 8.0–12.0 GHz. X-band have a wide range of applications of civil, military, weather monitoring, air traffic control, maritime vessel traffic control, defense tracking, and vehicle speed detection etc. each of the mentioned applications requires high performance sub-system stages such as bandpass filter [1], microwave absorber [2], high isolated MIMO Array [3], which are a thought-provoking topic for microwave engineers.

One of the most important elements in wireless communication systems is antenna with high gain characteristics. Although antenna arrays are a common solution since gain increase can be obtained with the increase of array element alongside high level of loss in feeding network which causes decrease in efficient, complexity of design. Another solution for high gain performance is usage of dielectric lens structures. Dielectric lens have been used for gain enhancements of microwave antennas due to their ability of focusing the incoming electromagnetic waves. Also, the dielectric lens antenna has advantages of low loss and wide operation band. These designs have been used in many applications such as millimeter wave, automotive radar, satellite or indoor communication applications [4-11], or are used to beam forming for generation of multiple beams [12-13]. However, widespread dielectric lenses like Luneburg, Einstein, dielectric rod, Fresnel lens are commonly optical or quasi-optical devices, which have 3D design structures that make them hard to fabricate with dielectric materials. However, with the advances in 3D printing technology, applications of these devices are increasing.

One of the most recent applications of 3D printing technology is prototyping of microwave designs such as

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antennas [14-16]. Due to their high accurate, fast printing ability even for the most complex structures whose prototyping by traditional methods becomes either impractical or costly, the interest to usage of 3D printing technology for microwave design prototyping become widespread [17-23].

Herein, it is aimed at designing and realizing a square shaped multi-layer lens for gain enhancement of a X-band traditional horn antenna using 3D printing technology. For this purpose, in the next section, firstly design procedure of the proposed multi-layer lens structure will be presented alongside of its simulated results. Then in Section 3, the antenna design will be prototyped via the use of 3D printing technology and its experimental results are compared with its simulated results and performance results of the counterpart designs in literature. Finally, the paper will end conclusion.

II. DESIGN AND SIMULATION

Horn antenna is one of the most commonly used antenna types in wireless communication systems such as astronomy, satellite tracking and high power RF systems [24]. Although they have a relatively good gain characteristics, they are limited by their dimension limitation where they should have a certain size with respect to their operation frequencies wavelengths, otherwise they would have efficiency problems. For the last decades many methods have been presented for performance improvement of horn antennas. Commonly hybrid designs had been presented to improve performance measures such as side lobe level, cross polarization [25-26], Corrugated horns [27–29], dielectric core horns [30], and strip-loaded horns [31] are the typical examples. Placement of dielectric lens structures to the aperture of antenna designs is one of the commonly used methods for performance improvement, where by placing the carefully selected materials and geometrical designs [32-35].

Herein, a squared shaped multi-layer dielectric lens (Fig. 1) is proposed as consisting of layers having variable heights and dielectric constants. In the design it should be noted that (i) the gain may be increased/ decreased by increasing/decreasing the dielectric width of the square layers; (ii) Operation frequency can be shifted via the width of layers; (iii) the dielectric constant of the lens material is also an important design parameter for focusing the EM waves [35-36].

In Table 1, geometrical values of the proposed designs are given. These values have been obtained by using a novel meta-heuristic optimization algorithm Invasive Weed Optimization (IWO). IWO is a population-based method inspired from the behavior of weed colonies that they search for an optimal environment to live [37]. IWO had shown great potential in application of; aperiodic planar thinned array antennas [38], the Shape of Non-Planar Electronically Scanned Arrays [39], directivity maximization of Uniform Linear Array of Half-wavelength Dipoles [40], Low Pass Elliptic Filter [41], Reflector Antenna [42] and design of a compact step impedance transmission line low pass filter [43]. Here similar to [44], an IWO algorithm coded in MATLAB environment has been used alongside of CST 3D EM simulator to obtain optimal performance criteria's based on the following cost function:

$$\text{Cost} = \sum_{f_{\min}}^{f_{\max}} \frac{C_1}{D_i(f)} + \frac{C_2}{\left|S_{11_i}(f)\right|}, \tag{1}$$

where C values have been found as $C_1=0.9$, $C_2= 0.3$ by trial and error [44]. Here the goal is to maximize both of the performance measures within the given operation band between f_{min}=8 GHz and f_{max}=12 GHz. Thus, both S_{11} and directivity D are optimized along the X-band using the cost function given by (1). In Fig. 2, a flow chart of the proposed design optimization process is presented.

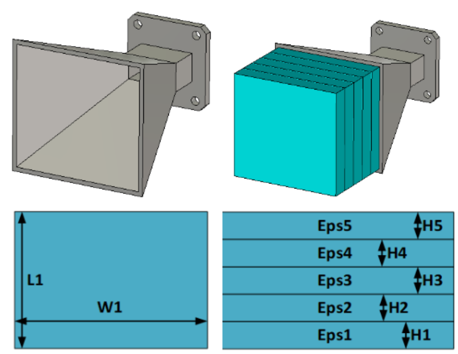


Fig. 1. Schematics of the proposed multi-layer squared lens antenna.

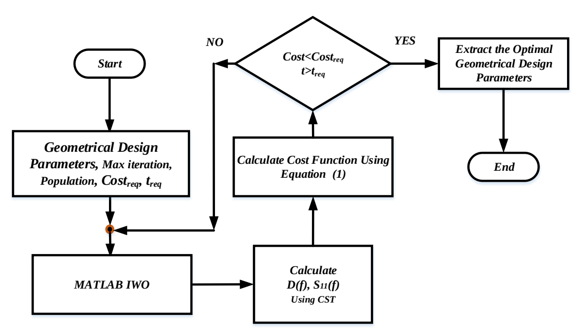
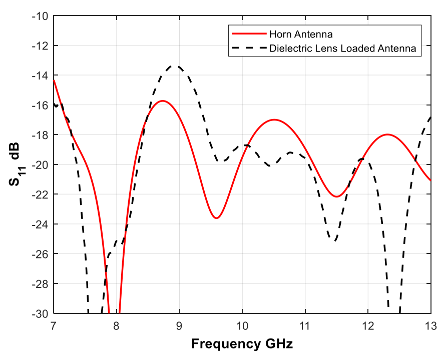


Fig. 2. Flow chart of the SIW antenna design optimization.

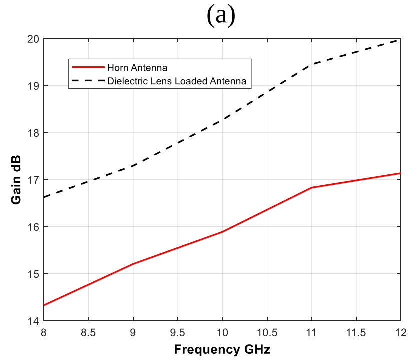
Table 1: Optimally selected design values

Eps1	1.66	**H1**	9.2 mm
Eps2	1.45	**H2**	10 mm
Eps3	1.15	**H3**	9.8 mm
Eps4	1.38	**H4**	9.9 mm
Eps5	2.1	**H5**	10 mm
L1	60mm	**W1**	60mm

In Fig. 3, the simulated performance of horn antenna with and without the multi-layer dielectric lens structure are presented. As it can be seen from the Fig. 2, not only the proposed design improves the overall radiation performance of the horn antenna over the operation band but also it has a low level of deteriorating on the performance of the return loss. A more detailed performance comparison of both antenna designs are presented in Table 2, where it can be clearly seen that the proposed dielectric lens antenna improves the realized gain characteristics up to 2.9dB over the aimed operation frequency.



(a)



(b)

Fig. 3. Simulated (a) return loss and (b) gain of horn antenna with and without dielectric lens structure.

Table 2: Simulated performances of horn/horn antenna equipped with multi-layer dielectric lens

f (GHz)	Realized Gain (dB)	Enhanced (dB)	3dB (Angle)	Side lobe level (dB)
8	14.4 / 16.6	2.2	32.1 / 25.5	-15.2 / -16.3
9	15.2 / 17.3	2.1	27.9 / 21.2	-12.5 / -12.6
10	15.9 / 18.3	2.4	26.4 / 19.7	-12.7 / -16.6
11	16.9 / 19.4	2.5	22.4 / 17.6	-11.3 / -14.7
12	17.1 / 20	2.9	22.3 / 16.6	-10.8 / -15.2

III. EXPERIMENT RESULTS

3D printing technology is one of the recent innovation that is being used for fast, accurate and low cost manufacturing of microwave devices [45]. Recently 3D printing technology has been applied for manufacturing of Multi-layered Cylindrical Dielectric Lens Antenna [36], Non-Uniform Reflectarrays [45], Quasi Yagi Antenna for indoor application [14], or prototyping of Horn Antennas for X-band applications [15], Electrically Small Spherical Wire Antennas [46].

In this section, the proposed multi-layer lens antenna has been prototyped via the use of a commercial 3D printer, CEL Robox® Micro manufacturing platform [47]. The 3D printer uses PLA material "PLA Filament - Polar White RBX-PLA-WH002" [48]. Thanks to the unique ability of 3D printer's infill rate adjustment, not only it allows to the lower weight of the designs but also it is possible to create dielectric materials with variable dielectric constant values [49-50]. Some cases of the PLA material with the different dielectric constants are presented in Table 3. The analytical expression in Eq. (2) between infill rate and dielectric constant is obtained via regression method using the experimental data given in Table 3:

$$\varepsilon_r = -1.3x10^{-6}x^3 + 0.0374x + \frac{6.42}{x} + 0.217, \quad (2)$$

where, x indicates the infill rate in %.

Table 3: Dielectric constant value of PLA with respect to the variant infill rate [49]

Infill Rate %	Dielectric Constant ε_r	Loss Tangent
18	1.24	0.002
33	1.6	0.004
73	2.53	0.006
100	2.72	0.008

The 3D printed multi-layer dielectric antenna and its measurement setup are presented in Fig. 4. A network analyzer with a measurement bandwidth of 9 KHz - 13.5GHz and a horn antenna [51] is used for the measuring the experimental results of the antenna.

Fig. 4. 3D printed antenna design.

The measured S_{11}, and radiation patterns of the 3D printed multi-layer dielectric lens antenna are given in Figs. 5-6 and Table 4. As it can be seen form Fig. 5, similar to the simulated results, placement of the 3D lens structure to the aperture of the antenna does not have any concerning distortive effect on the return loss performance. The design achieves a return loss characteristics of less than -10 dB over the operation band of 8-12 GHz. The measured radiation patterns of the proposed antenna with and without lens structure are presented in Fig. 6, and Table 4. From the measurement results it can be concluded that, just it was expected form the simulated results, the 3D printed lens structure increases the radiation performance of the antenna design 2.9 dB over the operation band of 8-12 GHz.

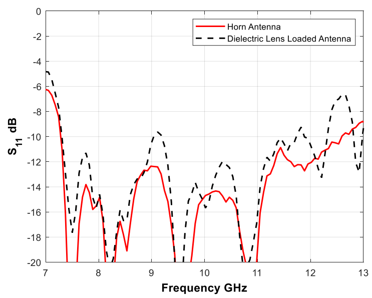
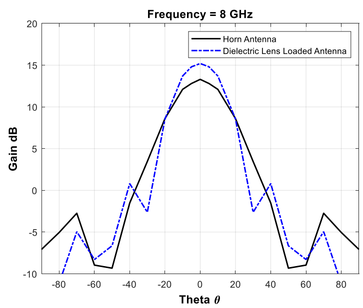
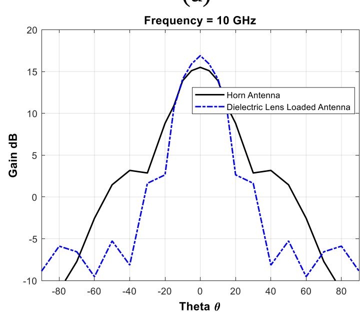


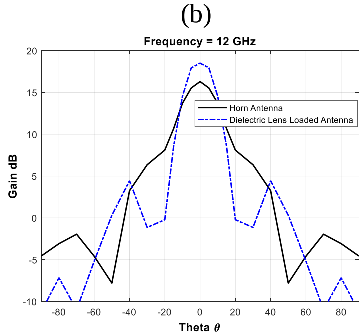
Fig. 5. Measured return loss.



(a)



(b)



(c)

Fig. 6. Measured radiation patterns of the prototyped antenna at: (a) 8 GHz, (b) 10 GHz, and (c) 12 GHz.

Table 4: Maximum gain (dB) comparison between simulation and measurement

Frequency (GHz)	**Simulated**	**Measured**
8	16.2	15.2
9	17.3	16.4
10	18.3	16.9
11	19.5	18.1
12	19.9	18.6

Table 5: Comparison of gain (dB) of typical dielectric loaded antenna modules

	Size (mm)	**Operation Band (GHz)**				
		8	**9**	**10**	**11**	**12**
Here	68x65x149	15.2	16.5	16.9	18.1	18.5
[52]	279x244x159	16	18	14.8	17	15
[53]	85.1x30.8x15.9	8.5	9	9	9	10
[54]	90.7x210x210	---	---	17	---	---
[55]	87.4x59.3x80	14	15.5	16.5	15	17

Furthermore a comparison of gain (dB) performance of the horn antenna equipped with multi-layer dielectric lens antenna with the counterpart designs in literature [42-55] has been presented in Table 5. From the comparisons, it can be concluded that the proposed dielectric lens structure can be used to model a high performance antenna that achieves better gain vs. size performance within the requested operation frequency compared to its counterpart designs.

VI. CONCLUSION

In this work, design and realization of a squared shaped multi-layer dielectric lens antenna via the use of 3D printing technology has been achieved. By using the unique features of 3D printing technology a dielectric lens structures with multiple layers that each has different values of substrate height and dielectric constant values are prototyped. By placing the proposed multi-layer dielectric lens stricter to the aperture of a traditionally horn antenna the gain performance of the antenna has been enhanced without deteriorating the return loss characteristics of the antenna over the selected operation up to 2.9dBi. Furthermore the experimental results of the prototyped antenna is compared with the counterpart dielectric loaded lens antenna designs in literature and found to be a better solution both in means of size and gain enhancement performance for the selected operation band.

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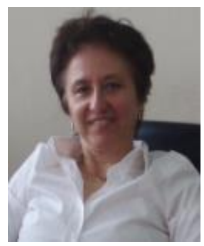

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