Realization of Modified Elliptical Shaped Dielectric Lens Antenna for X Band Applications with 3D Printing Technology

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Abstract **─** Placing dielectric lens structures into an antenna's aperture has proven to be one of the most reliable methods of enhancing its gain. However, the selected material and the prototyping method usually limit their fabrication process. With the advances in 3D printing technology and their applications, the microwave designs that were either impractical or impossible in the past to manufacture using traditional methods, are now feasible. Herein, a novel prototyping method by using 3D-printer technology for low-cost, broadband, and high gain dielectric lens designs has been presented. Firstly, the elliptical lens design has been modeled in the 3D EM simulation environment. Then fused deposition modeling based 3D-printing method has been used for the fabrication of the dielectric lens. The measured results of the 3D printed antenna show that the lens antenna has a realized gain of 17 to 20.5 dBi over 8-12 GHz. Moreover, the comparison of the prototyped antenna with its counterpart dielectric lens antenna in the literature has indicated that the proposed method is more efficient, more beneficial, and has a lower cost.

Index Terms **─** 3D Printer, Lens Antenna, Dielectric Lens, Broadband, Novel Prototyping Methods.

I. INTRODUCTION

One of the essential components in wireless communication systems is antenna stages with high gain characteristics. Although Antenna Arrays are a standard solution for high gain performance, it is known that increasing the array element directivity also increases the complexity of its design, decreases its efficiency, and leads to a higher level of loss in the feeding network. On the other hand, dielectric lens structures, having the ability to focus the incoming electromagnetic waves, provide another solution for high gain performance. Dielectric lens antennas are not only free from the disadvantages of Antenna Arrays but also advantageous due to their low loss and wide operation band. Moreover, these designs have been used in a vast range of applications such as millimeter wave, automotive radar, satellite or indoor communications [1-8], beamforming, and generation of multiple beams [9-10]. However, some of the most commonly used dielectric lens structures such as Luneburg, Einstein, dielectric rod, and Fresnel lens are usually optical or quasi-optical, and they have a 3D design structure that makes them difficult to manufacture by using dielectric materials.

With the advances in 3D printing technology, the application areas of these devices continue to expand. One of the most recent applications of 3D printing technology is the prototyping of microwave designs such as Antennas [11-13]. Due to being fast, highly accurate, and their ability to print even the most complex structures which would become either impractical or high cost using traditional prototyping methods, the usage of 3D printing technology has become more prevalent in microwave design prototyping field [14-20].

In this paper, the design and realization of a modified elliptical lens antenna for X band applications by using 3D printing technology has been presented. To this aim, first, elliptical lens design has been modeled in the 3D EM simulation environment. Then, the optimally designed elliptical lens model has been prototyped by using 3D printing technology. The measurements and the simulations show that the proposed prototyped elliptical lens antenna has a desirable performance where it achieves a gain level of 17 to 20.5 dBi over the operation band of 8-12 GHz. Moreover, when it is compared with its counterpart in literature, it is found that the proposed method is more efficient, has a lower cost, and it is an effective method for prototyping dielectric lens structures with 3D properties.

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II. DESIGN AND SIMULATION OF DIELECTRIC LENS ANTENNA

One of the most commonly used antenna types is a waveguide horn antenna. Although they have relatively good gain characteristics, they are limited by their dimensions as they must have a specific size with respect to the wavelength of their operating frequency. Otherwise, they would have efficiency problems. One of the solutions to go beyond this limitation and improve their performance is to place a dielectric lens structure into their aperture.

In this section, an elliptical lens antenna is designed for X band applications. The elliptical dielectric structure is a modified version of the lens design in [21-22], where the endpoint of the structure is trimmed to increase the performance of the antenna in the X band. The design of the Modified Elliptical Dielectric Lens Antenna (MEDLA) is given in Fig. 1. The primary design considerations of the proposed antenna can be named as follows:

(i) Gain performance of the antenna can be increased/decreased by increasing/decreasing the dielectric diameter of the ellipsoid.

(ii) The operating frequency can be increased/ decreased by decreasing/increasing all dimensions of the model.

(iii) Same phenomena can also be said for the dielectric permittivity of the lens material, which plays an essential role in the performance characteristic of the design.

Furthermore, by adding additional matching layers, the reflections at the antenna surface can be reduced at the expanse of increasing the manufacturing cost.

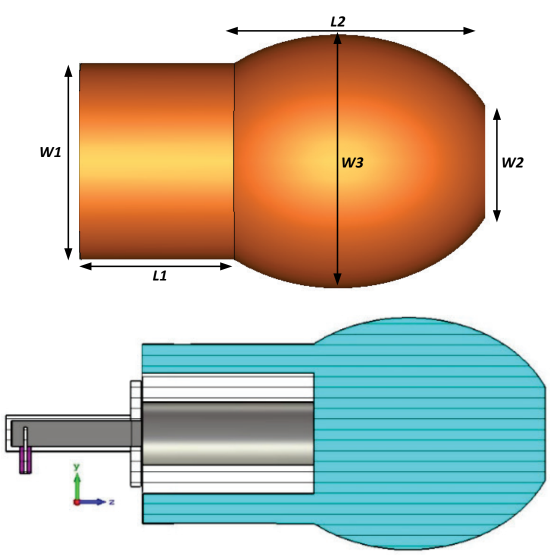
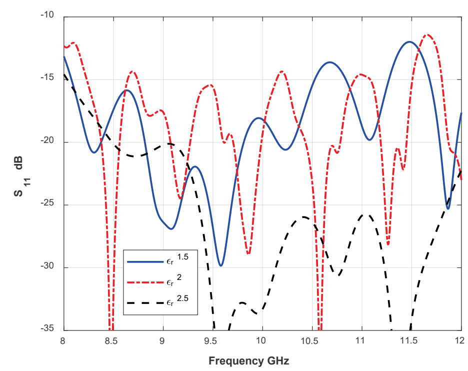


Fig. 1. Schematic of MEDLA.

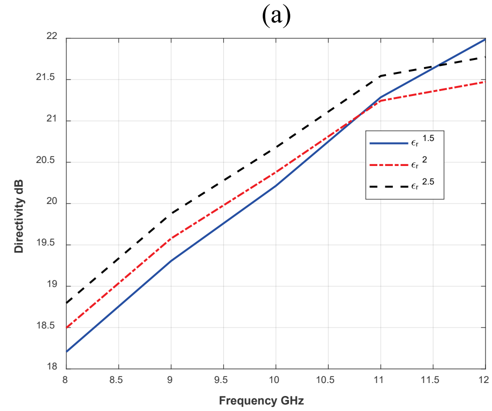
The variation of Directivity and S_{11} performances of the MEDLA concerning its design parameters are given in Table 1 and Fig. 2.

Table 1: Parametric analyses of design parameters of MEDLA given as (S_{11}/Directivity)

Parameters (mm)		Frequency GHz 8	10	12
L_1	50	-13.6/18.9	-17.9/20.1	-19.2/21
	70	-14.1/18.9	-17.7/20.2	-19.7/21
	90	-3/19.1	-5.3/20.2	-20.5/21.4
L_2	80	-6.5/16.8	-9/18.8	-10.7/19
	100	-14.1/18.9	-17.1/20.2	-19.7/21.1
	120	-7.6/17.8	-8.6/19	-9.1/18.1
W_1	50	-14.1/19	-18/20.3	-19.4/21
	70	-14.1/18.9	-17.8/20.2	-19.8/21.1
	90	-14.8/19.1	-17.8/20.3	-20.6/21.1
W_2	10	-15/18.9	-17.8/20.2	-19.8/21.1
	20	-14.1/18.9	-17.7/20.3	-19.8/21.2
	30	-13/18.9	-18/20.3	-20.8/21.2
W_3	60	-6.5/18.8	-8.7/20.2	-9/20.6
	80	-14.1/18.9	-17.7/20.2	-19.7/21.4
	100	-6.1/18.5	-8.9/19.9	-12.7/21.4



(a)



(b)

Fig. 2. Simulated performance of: (a) return loss and (b) Directivity; for variant dielectric constant values.

As can be seen from Table 1 and Fig. 2, each design parameter has a unique effect on the performance response of MEDLA design. Thus, the determination of optimal design parameters of antennas geometrical and material parameters can be considered as a multi-objective, multivariable optimization problem. The design parameters of MEDLA can be taken as input variables of the optimization process, and the performance measures of MEDLA, such as S11 and directivity, are taken as outputs or objectives of the optimization problems. In Table 2, optimization variables and their upper and lower constants are presented.

Table 2: Constraints of the variables

Parameter	Constraint	Parameter	Constraint
w_1 *(mm)*	50~90	***L_1* (mm)**	50~90
w_2 *(mm)*	10~30	***L_2* (mm)**	80~100
w_3 *(mm)*	60~100	ε_r	1.2~2.7

In our design process, two metaheuristic optimization algorithm that had shown great potential in design optimization of microwave stages; (1) Honey Bee Mating Optimization (HBMO) [23-24], (2) Differential Evolutionary Algorithm (DEA) [25-26], are being used in a hybrid combination of Global (HBMO) and Local (DEA) search tool for finding the optimal design parameters of MEDLA. HBMO algorithm has the capability of searching in ample variables space, which makes it an excellent global optimizer. However, the design optimization of an antenna requires a fine-tuning of design parameters for achieving the ideal performance. For this mean, the DEA optimization method had been used to do a local search around the optimal values obtained by HBMO. Both of the algorithms had been coded in MATLAB environment that can simultaneously work alongside CST simulator [27]. Based on the designer's hardware capabilities, this process can be accelerated via the use of parallel processing methods for reducing the total time required. The cost function that is given in Eq (1) is being used for guiding the hybrid search of HBMO and DEA. The total cost is calculated based on the candidate solution's directivity and S_{11} values at each desired frequency:

$$\text{Cost}_i = \sum_{f=8\text{GHz}}^{12\text{GHz}} \frac{C_1}{Directivity(f)_i} + \frac{C_2}{\left|S_{11}(f)_i\right|}, \tag{1}$$

where, C is weighted constrained determined by the user (Here in C_1=0.9, C_2= 0.3, which is determined with trial and error method), i is the index of the candidate solution in search space. In Table 3, the optimal design parameters of MEDLA have been presented.

Table 3: Parameters of MEDLA in (mm)

W_1	70	***L_1***	67.5
W_2	20	***L_2***	95.8
W_3	84	ε_r	2.5

III. 3D MANUFACTURING AND EXPERIMENTAL RESULTS OF MEDLA

In this section, the CEL Robox® Micro manufacturing platform using PLA material "PLA Filament - Polar White RBX-PLA-WH002" is employed for carrying out the prototyping of the MEDLA designed in Section II. One of the advantages of 3D printers is their ability to adjust the infill rate of the printed material within the structure, which is used by many for creating a design with lower weight values. In addition, making use of this advantage, it is possible to adjust the dielectric properties of the 3D printed structure by increasing or decreasing the infill rate of the design as it is given in Table 4 [28-29]. By using the Eq (2) obtained via regression methods from data in Table 4, the infill rate of the MEDLA is chosen as 70%, which would provide a dielectric constant value of 2.5:

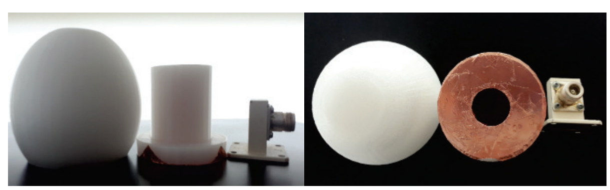
$$\varepsilon_r = -1.3x10^{-6}x^3 + 0.0374x + \frac{6.42}{x} + 0.217, \tag{2}$$

where x indicates the infill rate in %.

Table 4: Dielectrıc constant value of PLA with respect to the infill rate [28]

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 MEDLA design is presented in Fig. 3. The measurement results are obtained using the measurement setup given [30-31]. A Network Analyzer with a measurement bandwidth of 9 kHz to 13.5 GHz, and two identical antennas "Rohde—Schwarz RS Zvl13 and LB8180 0.8 to 18 GHz" have been used for measurement of the 3D printed Dielectric Lens antenna.



(a) (b)

Fig. 3. Dielectric lens antenna and feed network: (a) side view and (b) top view.

The measured return loss characteristics are given in Fig. 4. It can be observed in Fig. 4 that placing the 3D printed elliptical lens structure into the aperture of the waveguide does not have any distortive effects on the S_{11} characteristics of the system, and the design achieves return loss characteristics of less than -10 dB over the operation band of 8-12 GHz. In addition, it should also be noted that the main reason for the difference between the simulated and the measured S_{11} characteristics is that the simulations were carried out by assuming an ideal waveguide, whereas non-ideal real waveguides are used for the measurements.

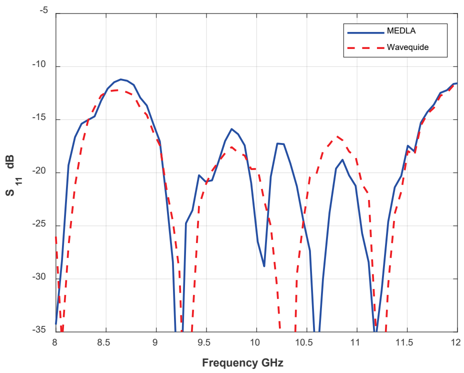
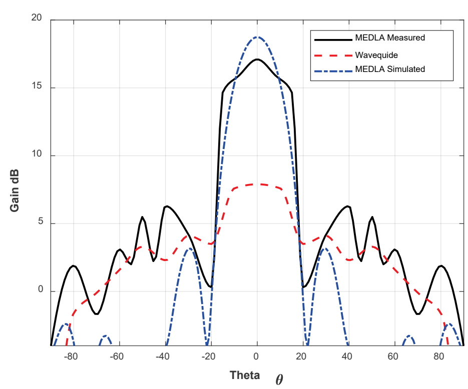


Fig. 4. The measured return loss of MEDLA.

The radiation patterns of the 3D printed MEDLA and the comparison of the maximum gain values between the simulations and the measurements are given in Fig. 5 and Table 5, respectively. It can be concluded from the measurement results shown here that the 3D printed MEDLA structure increases the directivity of the waveguide up to 11 dB over the operation band of 8-12 GHz.



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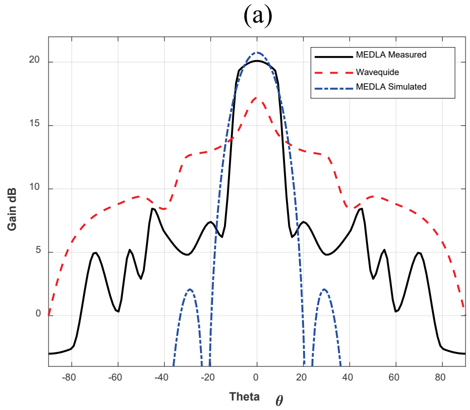

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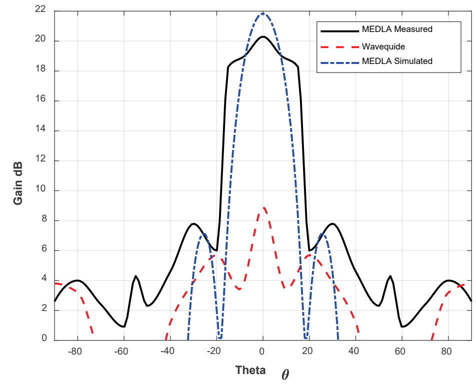


(c)

Fig. 5. Measured and simulated radiation patterns of the MEDLA at: (a) 8 GHz, (b) 10 GHz, and (c) 12 GHz.

Table 5: Maximum hgain (dB) comparison between simulation and measurement

f GHz)	MEDLA		Waveguide
	Simulated	Measured	
8	18.7	17.1	7.9
9	19.8	18.2	8.2
10	20.7	19.8	8.7
11	21.5	20.5	9
12	21.8	20.3	8.9

Furthermore, a gain (dB) comparison of the proposed MEDLA design with similar works in literature [32-35] is given in Table 6. As can be seen from the comparison table, the proposed antenna design achieves a high wideband gain performance compared to the counterpart designs in [32,34], where designs have much larger sizes. In cases of [33, 35] where the designs have much smaller sizes, the gain performance is almost half [35], or much lesser [35] than of the proposed MEDLA design. Thus, it can be said that the proposed MEDLA module achieves a more desirable Gain vs. Volume performance within the requested operating frequency compared to its counterpart designs.

Table 6: Comparison of gain (dB) of typical dielectric loaded antenna modules

	Size (mm)	Volume cm^3	Operation Mand (GHz)				
			8	9	10	11	12
Here	163.3x70x84	960.2	17.1	18.2	19.8	20.5	20.3
[32]	279x244x159	10824	16	18	14.8	17	15
[33]	85.x30.8x15.9	41.62	8.5	9	9	9	10
[34]	90.7x210x210	4013	---	---	17	---	---
[35]	87.4x59.3x80	414.6	14	15.5	16.5	15	17

VII. CONCLUSION

Herein, a modified elliptical lens antenna was designed for X band applications and realized by using

3D printing technology. The optimally designed elliptical lens model was prototyped by using 3D printing technology, and then its simulated and measured performance were compared. The results were found to be desirable, where the proposed prototyped elliptical lens antenna achieves a gain level of 17 to 20.5 dBi over the operation band of 8-12 GHz. In addition, the comparison of the prototyped antenna with its counterpart dielectric lens antenna in literature proved that the proposed method is more efficient, has a lower cost, and it is an effective method for prototyping dielectric lens structures with 3D properties. Thanks to the unique manufacturing capability of 3D printers and varying permittivity values of materials concerning their infill rates, it is possible to have elliptical or non-uniform geometrical designs for dielectric lens stages with multiple layers with different dielectric constant values. Furthermore, with recent developments in 3D printing materials such as conductive filaments, the design of multi-material-lens stages can also be achieved.

REFERENCES

[1] J. R. Risser, *Microwave Antenna Theory and Design*. New York, NY, USA: McGraw-Hill, 1949.

[2] B. Chantraine-Bares, R. Sauleau, L. L. Coq, and K. Mahdjoubi, "A new accurate design method for millimeter-wave homogeneous dielectric substrate lens antennas of arbitrary shape," *IEEE Trans. Antennas Propag*., vol. 53, no. 3, pp. 1069-1082, Mar. 2005.

[3] W. E. Kock, "Metallic delay lens," *Bell System Tech. J*., vol. 27, pp. 58-82, Jan. 1948.

[4] W. E. Kock, "Metal lens antennas," *Proc. IRC*, vol. 34, no. 11, pp. 826-836, Nov. 1946.

[5] B. Schoenlinner, X. Wu, J. P. Ebling, G. V. Eleftheriades, and G. M. Rebeiz, "Wide-scan spherical-lens antennas for automotive radars," *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 2166-2175, 2002.

[6] B. Fuchs, O. Lafond, S. Rondineau, M. Himdi, and L. Le Coq, "Off-axis performances of half Maxwell fish-eye lens antennas at 77GHz," *IEEE Trans. Antennas Propag.*, vol. 55, pp. 479-482, 2007.

[7] J. R. Costa, C. A. Fernandes, G. Godi, R. Sauleau, L. Le Coq, and H. Legay, "Compact Ka-band lens antennas for LEO satellites," *IEEE Trans. Antennas Propag*., vol. 56, pp. 1251-1258, 2008.

[8] C. A. Fernandes, "Shaped dielectric lenses for wireless millimeter-wavecommunications," *IEEE Antennas Propag. Mag*., vol. 41, pp. 141-150, 1999.

[9] O. Lafond, M. Caillet, B. Fuchs, S. Palud, M. Himdi, S. Rondineau, and L. Le Coq, "Millimeter wave reconfigurable antenna based on active printed array and inhomogeneous lens," 2008 38th *Eur. Microwave Conf*., Amsterdam, Holland, pp. 147-150, 2008, doi: 10.1109/EUMC.2008.4751409.

[10] B. Fuchs, S. Palud, O. Lafond, M. Himdi, and S. Rondineau, "Système antennaire dont le diagramme de rayonnement est reconfigur-able parmi des diagrammes de rayonnement sectoriels et directifs, etdispositifs émetteur et/ou récepteur correspondant," French Patent 0756664, July 20, 2007.

[11] M. A. Belen and P. Mahouti, "Design and realization of quasi Yagi antenna for indoor application with 3D printing technology," *Microw. Opt. Technol. Lett*., vol. 60, no. 9, pp. 2177-2181, 2018. https://doi.org/10.1002/mop.31319

[12] Y. C. Toy, P. Mahouti, F. Güneş, and M. A. Belen, "Design and manufactering of an X-band horn antenna using 3-D printing technology," *8th International Conference on Recent Advances in Space Technologies*, İstanbul, Turkey, June 19-22, 2017.

[13] J. J. Adams, E. J. Duoss, T. Malkowski, M. Motala, B. Y. Ahn, R. G. Nuzzo, J. T. Bernhard, and J. A. Lewis, "Conformal printing of electrically small antennas on three-dimensional surfaces," *Advanced Materials*, vol. 23, no. 11, pp. 1304-1413, 2011.

[14] G. Shaker, L. Ho-Seon, S. Safavi-Naeini, and M. Tentzeris, "Printed electronics for next generation wireless devices," *IEEE Antenna and Propagation Conference (LAPC)*, pp. 1-5, Nov. 2011.

[15] J. Mei, M. Lovell, and M. Mickle, "Formulation and processing of novel conductive solution inks in continuous inkjet printing of 3-D electric circuits," *IEEE Transactions on Electronics Packaging Manufacturing*, vol. 28, no. 3, pp. 265-273, July 2005.

[16] G. Shaker, S. Safavi-Naeini, N. Sangary, and N. M. Tentzeris, "Inkjet printing of ultrawideband (UWB) antennas on paper based substrates," *Antennas and Wireless Propagation Letters, IEEE*, vol. 10, pp. 111-114, 2011.

[17] J. Hester, S. Kim, J. Bito, T. Le, J. Kimionis, D. Revier, C. Saintsing, W. Su, B. Tehrani, A. Traille, B. S. Cook, and M. Tentzeris, "Additively manufactured nanotechnology and origami-enabled flexible microwave electronics," *Proc. IEEE*, vol. 103, no. 4, pp. 583-606, Apr. 2015.

[18] J. Kimionis, A. Georgiadis, M. Isakov, H. J. Qi, and M. M. Tentzeris, "3D/inkjet-printed origami antennas for multi-direction RF harvesting," *in IEEE MTT-S Int. Microw. Symp. (IMS)*, Phoenix, AZ, USA, pp. 1-4, May 2015.

[19] C. D. Saintsing, K. Yu, H. J. Qi, and M. Tentzeris, "Planar monopole antennas on substrates fabricated through an additive manufacturing process," *2015 IEEE Radio and Wireless Symposium (RWS)*, San Diego, CA, pp. 159-161, 2015. doi: 10.1109/

RWS.2015.7129744.

[20] B. Tehrani, B. S. Cook, and M. M. Tentzeris, "Post-process fabrication of multilayer mm-wave on-package antennas with inkjet printing," in *2015 IEEE Int. Symp. Antennas and Propag. (APSURSI)*, Vancouver, BC, Canada, July 2015.

[21] N. Pohl, "A dielectric lens antenna with enhanced aperture efficiency for industrial radar applications." Available on https://www.cst.com/solutions/article/a-dielectric-lens-antenna-with-enhanced-aperture-efficiency-for-industrial-radar-applications

[22] N. Pohl, "A dielectric lens antenna with enhanced aperture efficiency for industrial radar applications," in *IEEE Middle East Conference on Antennas and Propagation (MECAP 2010)*, pp. 1-5, Oct. 2010.

[23] F. Güneş, S. Demirel, and P. Mahouti, "A simple and efficient honey bee mating optimization approach to performance characterization of a microwave transistor for the maximum power delivery and required noise," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 29, no. 1, pp. 4-20, 2016.

[24] F. Güneş, S. Demirel, and P. Mahouti, "Design of a front–end amplifier for the maximum power delivery and required noise by HBMO with support vector microstrip model," *Radioengineering*, vol. 23, no. 1, pp. 134-143, 2014.

[25] F. Güneş, M. A. Belen, and P. Mahouti, "Competitive evolutionary algorithms for building performance database of a microwave transistor," *International Journal of Circuit Theory and Applications*, vol. 46, no. 2, pp. 244-258, 2018.

[26] P. Mahouti, "Design optimization of a pattern reconfigurable microstrip antenna using differential evolution and 3D EM simulation-based neural network model," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 29, no. 8, e21796, 2019.

[27] A. Belen, F. Güneş, and P. Mahouti, "Design optimization of a dual-band microstrip SIW antenna using differential evolutionary algorithm for X and K-band radar applications," *ACES Journal*, Accepted.

[28] S. Zhang, C. C. Njoku, W. G. Whittow, and J. C. Vardaxoglou, "Novel 3D printed synthetic dielectric substrates," *Microw. Opt. Technol. Lett*., vol. 57, pp. 2344-2346, 2015. doi:10.1002/mop.29324.

[29] P. Mahouti, "3 Boyutlu Yazıcı Teknolojisi ile Bir Mikroşerit Yama Antenin Maliyet Etkin Üretimi," *Journal of Engineering Sciences and Design*, Kabul Edildi, 2019 (in Turkish).

[30] F. Güneş, Z. Sharipov, M. A. Belen, P. Mahouti, "GSM filtering of horn antennas using modified double square frequency selective surface," *Int. J. RF Microw. Comput. Aided Eng*., vol. 27, e21136, 2017. https://doi.org/10.1002/mmce.21136

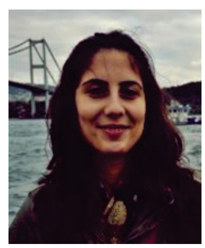
[31] M. A. Belen, F. Güneş, P. Mahouti, and A. Belen, "UWB gain enhancement of horn antennas using miniaturized frequency selective surface," *ACES Journal*, vol. 33, no. 9, Sep. 2018.

[32] A. S. Türk, A. K. Keskin, and M. D. Şentürk, "Dielectric loaded TEM horn-fed ridged horn antenna design for ultrawideband ground-penetrating impulse radar," *Turkish J. Elec. Eng. & Comp. Sci*., vol. 23, pp. 1479-1488, 2015.

[33] R. J. Bauerle, R. Schrimpf, E. Gyorko, and J. Henderson, "The use of a dielectric lens to improve the efficiency of a dual-polarized quad-ridge horn from 5 to 15 GHz," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 6, June 2009.

[34] J. Tak, D.-G. Kang, and J. Choi, "A lightweight waveguide horn antenna made via 3d printing and conductive spray coating," *Microwave and Optical Technology Letters*, vol. 59, no. 3, Mar. 2017.

[35] M. F. Ain, A. Othman, and Z. A. Ahmad, "Hybrid dielectric resonator integrated pyramidal horn antenna," *Microwave and Optical Technology Letters*, vol. 55, no. 6, June 2013.



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