Experimental Assessment of the Performance of Meta-resonator Based Band-stop Waveguide Filters Fabricated with CNC Milling and Stereolithography Methods

SINAN BICER[1], ABDULRAHMAN NASSER ABASS ABDO[2], HABIB DOGAN[3], ABDULLAH GENC[2]
[1]Department of Electricity and Energy,
Akdeniz University,
Antalya,
TURKEY

[2]Department of Mechatronics Engineering,
Isparta University of Applied Sciences,
Isparta,
TURKEY

[3]Department of Computer Technology and Information Systems,
Burdur Mehmet Akif Ersoy University,
Gölhisar, Burdur,
TURKEY

Abstract: - In this work, using SRR meta-resonators, a band-stopping waveguide filter (WGF) in C band (4-7.5 GHz) is designed and fabricated by using both CNC milling and SLA methods, and the effect of the fabrication methods on the filter performance is experimentally evaluated. The filter order for each case is increased from 1 to 7 and meta-resonators are used as many as the number of filter degrees. To determine the performance of the WGFs, some results such as frequency response, center frequency, fractional bandwidth (FBW), and quality factor (Q) values are given comparatively for each filter order. Also, the simulated and measurement results are in good agreement with each other. The measured results show that the performance of the WGFs fabricated by the CNC milling method is partially better than the filter fabricated by the SLA method. This decrease in SLA performance is thought to be due to the production methods. However, The WGF with the SLA method is nearly 50% lighter in weight than that produced with the CNC method. As a result, the SLA fabrication method is experimentally demonstrated to be a good alternative to conventional fabrication methods such as CNC milling.

Key-Words: - Waveguide Filters, CNC Milling, Split Ring Resonator (SRR), Stereolithography, Metal Coating.

Received: April 28, 2024. Revised: October 29, 2024. Accepted: November 29, 2024. Published: December 27, 2024.

1 Introduction

Developing communication techniques has led to more miniaturized and more complex devices. For this reason, efforts to produce communication equipment in smaller sizes without losing their performance are increasing day by day, [1], [2], [3], [4]. Filters, which are indispensable elements of the communication industry, are one of the equipment that need to be miniaturized. In particular, the size and weight problems of conventional waveguide filters (WGF), which are used extensively in areas such as radar, satellite communications, etc., must be solved. WGFs have advantages over other filter types regarding high power handling and low loss performance. However, the biggest problem with these filter types is their large size, [2].

Conventional WGFs are obtained by placing post and iris structures in a waveguide (WG). In order to reduce the size of WGF filters, different dielectric materials have been added to the WG, different cavity techniques have been tried, and electrical sizes have been reduced to provide the required performance at the desired frequencies, [3], [4]. Recently, in addition to these techniques, meta-resonators, an application of metamaterials, have been used to create WGFs. Meta-materials are structures that enable the material to exhibit the opposite behavior of its dielectric properties with designed geometries [5], and have recently been used in many different areas of communication systems, [6], [7], [8], [9]. Meta-resonators allow the creation of desired LC values that determine the operating parameters of the filter with different geometries and allow filter design in a much easier way. Depending on the type of designed meta-resonator (Complimentry Split Ring Resonator (SRR)/Split Ring Resonator (SRR)), band-pass and band-stop WGFs can be obtained. The fact that they are easier to design and fabricate than conventional filters and that they allow flexibility in the parameters that determine the filter performances make them stand out in this field, [10], [11], [12].

In addition, WGFs, which are traditionally produced mostly by CNC milling, can be very costly compared to the lower manufacturing tolerance to meet the desired parameters. For this, different fabrication methods such as 3D printing should be evaluated in terms of both cost and weight. Therefore, stereolithography (SLA) additive manufacturing techniques offer remarkable alternatives. This is because the surface roughness of the part produced in this fabrication method is low compared to other methods. The parameters that most affect the performance of passive microwave components such as filters, WGs, and antennas are metal conductivity and surface roughness, [13], [14], [15]. It is well-known that structures produced using additive manufacturing methods with lower surface roughness such as SLA can be easily used in WGFs design by metal coating, [16], [17], [18]. After the proposed structure is produced by 3D printing, a homogeneous metal coating process should be applied to the entire surface. During this coating process, the thickness of the metal layer should be thicker than the skin depth. To prevent oxidation and tarnishing after metal coating, the part should be protected with a thin layer after mapping for a longer life, [19].

In this study, a meta-resonator based band-stop waveguide filter at C-band (4-7.5 GHz) is designed and evaluated by comparing simulation and measurement results. The proposed WGF are fabricated using both the CNC method and SLA technique, and the performances of the fabrication methods on the filter are tested and experimentally assessed. The filter order for each case is increased from 1 to 7 and meta-resonators are used as many as the number of filter degrees. In order to determine the performance of the filters, some results such as frequency response, center frequency, fractional bandwidth (FBW), and quality factor (Q) values are given comparatively for each filter order. In addition, the CNC Milling and SLA fabrication methods used to obtain the proposed structure are explained in detail. The simulated results are verified with measured results and it is concluded that 3D printing techniques can be considered as an alternative solution to conventional methods. Moreover, the study is organized as follows: Section 2 presents the design and fabrication of the SRR-based band-stop WGFs. In Section 3, the simulation and measurement results are analyzed and the results of the study in the conclusion (Section 4) are discussed in detail.

2 Design and Fabrication of the SRR based Band-Stop Waveguide Filters

2.1 The Design of the Proposed Filters

The proposed filter structure consists of two parts; the novel WG structure and SRR meta-resonators. Firstly, the WG structure is designed using the WR-159 (4.90-7.05 GHz) rectangular waveguide. The internal dimensions of the WR-159 WG are determined as 20.193×40.386×100 mm^3 ($a \times b \times l$). CPR-159G model flange is used as flange type. In order to place the meta-resonators within the WR-159 waveguide, groove parts inside the waveguide are added with the thickness (t_{sub}=1.57 mm) of the meta-resonator, which is made by RT/Duroid® 5880 substrate. The designed SRR meta-resonators with rectangular geometry and the placement of meta-resonators within the WR-159 waveguide are depicted in Figure 1. Accordingly, RT/Duroid® 5880 material with a dielectric constant of 2.20 and a loss tangent ($tan\delta$) of 0.0009 is preferred because of its low loss. In Figure 1(a), the dimensions of the SRR structure are accurately designed with the help of an "optimizer" in the simulation program with a center frequency of 6 GHz. The design parameters of SRR meta-resonators are given in Table 1. The equivalent circuit model of the designed SRR meta-resonator structure can be expressed as a parallel LC circuit. In this study, all simulations are carried out numerically in CST Microwave Studio (MWS) in Figure 1(b). The filter with two ports is excited by waveguide port and boundary.

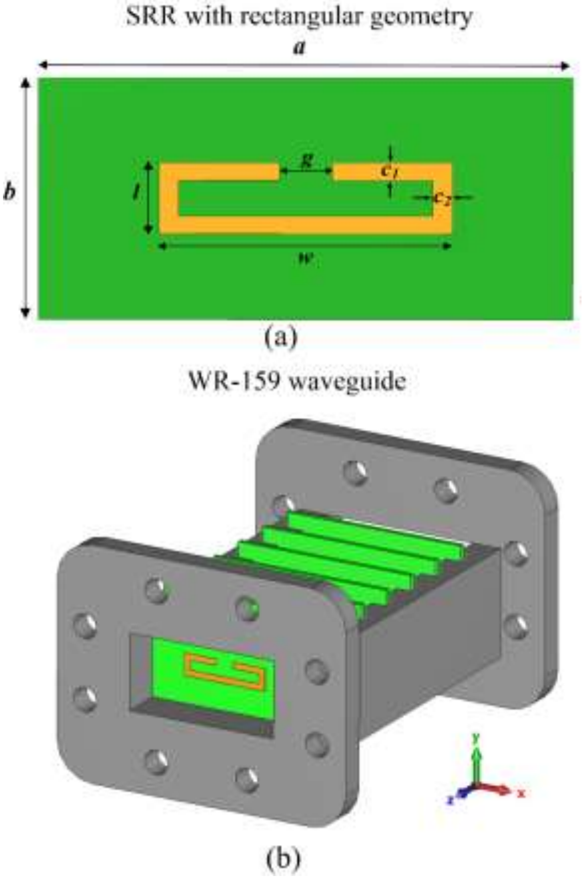

Fig. 1: (a) The designed SRR meta-resonators with rectangular geometry, and (b) the placement of SRR meta-resonators within the WR-159 waveguide

Table 1. The design parameters of SRR meta-resonators

Meta-resonator	Parameters	Dimensions (mm)
SRR with rectangle geometry	l	5.909
	g	4.7
	w	22.578
	c_1	1.65
	c_2	1.65

2.2 The Fabrication of the Proposed Filters and Measurement Setup

The proposed WGF structure fabricated by the CNC Milling method is depicted in Figure 2. The designed structure is precisely manufactured by First MCV-800 brand CNC milling machine. To avoid any electromagnetic (EM) leakage outward from the inside, the upper part of the structure is fabricated with a 45-degree inclination, and the structure is tightly assembled with the help of screws. On the other hand, the filter fabrication obtained using the 3D printing method takes place in two stages. These are the fabrication of the designed CAD model by the SLA printing method and metal coating of all surfaces of the structure. First of all, the proposed structure is produced with an Elegoo Saturn 3 Ultra 12k model SLA printer using liquid resin. In the SLA printing process, the print settings are important for the part to be printed properly. In this study, the print settings are made with the Chitu Box program. The two most important parameters in the print settings are layer height and normal exposure time, which are set as 0.05 mm and 2.5 s, respectively. After the SLA printing process is completed, the metal coating process of the surfaces of the part is performed. In the WGFs shown in Figure 2(b), the coating process consists of three parts: pretreatment, metal coating process, and varnishing process. All coating processes are carried out by spraying method and finally, varnish is applied to prevent oxidation (Figure 2(b)).

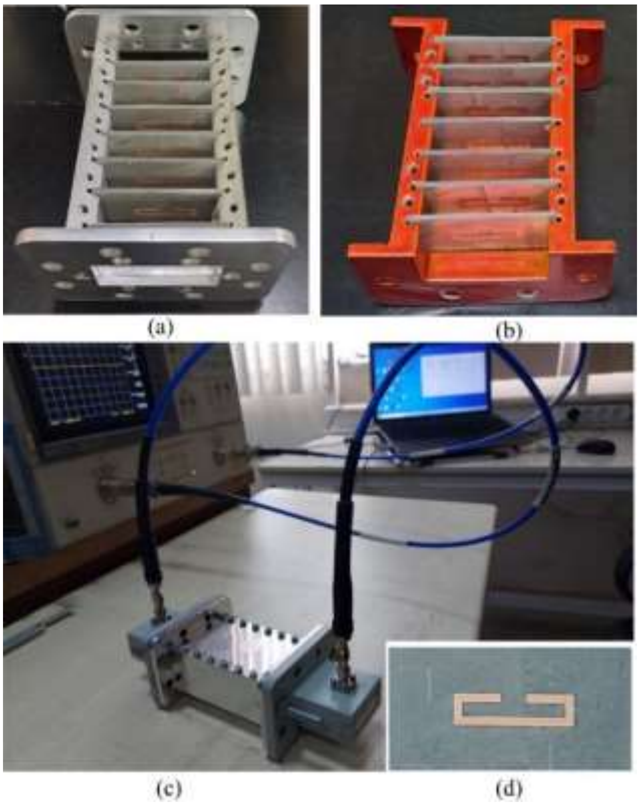

Fig. 2: (a) The proposed filters fabricated by CNC Milling, (b) the filters fabricated by stereolithography and metal plating, (c) measurement setup, and (d) the designed SRR meta-resonator etched with LKPF device

The meta-resonator structure is etched via the LPKF ProtoLaser U4 model LKPF device. The central frequency of the filter at the desired value (at 6 GHz) depends on the technical specifications of the engraving device being sufficient. If the SRR meta-resonator dimensions determined in the design are not adhered to in the fabrication, the LC load values in the equivalent circuit of the meta-resonator may shift undesirably. For this reason, the meta-resonator in Figure 2(d) is accurately fabricated. Furthermore, the measurement setup is depicted in Figure 2(c) and the S-parameters for the different filter orders are measured between 4-7.5 GHz using a vector network analyzer (VNA). The S-parameters are measured at the Industrial and Medical Applications Microwave Research and Application Center (EMUMAM) of Akdeniz University. In all measurements, an HP Hewlett Packard brand 8720C model network analyzer (VNA) operating in the range of 50 MHz-20 GHz is used. In addition, the Short-Open-Load-Through calibration (SOLT) calibration method is utilized to eliminate systematic errors in the measurement setup. This method is also known as a reference method that can demonstrate the accuracy of measurement methods.

3 Simulation and Measurement Results

The frequency responses of the proposed band-stop waveguide filters for various filter orders are given in Figure 3. Accordingly, simulated and measurement results have good agreement with each other. In general, the performance of the CNC-fabricated filter is slightly better than that of the SLA-fabricated filter in all filter orders. This is thought to be due to losses due to the thin varnish used on the metal coating to prevent oxidation. Apart from this, another reason may be the small amount of EM leakage that occurs in the mounting areas of the WGF. All filters designed in this study have a center frequency of 6 GHz and are band-stop filters with approximately 6-7% FBW. As the filter degree increases from 1 to 7, the selectivity of the filter increases and this is a desirable result. However, as the filter order increases, both the number of meta-resonators used and the electrical/dielectric losses increase, which is a drawback.

The EM losses increase depending on the filter degree, as expected. Compared to the 6 GHz center frequency obtained in the simulation results, the measured center frequencies from both SLA and CNC milling methods shift very slightly. This is due to manufacturing defects of the meta-resonator and these defects are negligible. As can be seen from Table 2, the FBW values are 7.23%, 6.88%, 6.36%, and 6.15% for the 1st, 3rd, 5th, and 7th order filter values, respectively. The WGFs bandwidths are approximately the same, and different types of SRR geometry (ring, crescent) should be used to obtain filters with different bandwidths rather than the filter degree. Furthermore, the measured *Q* values range between 14.97-19.11 for the CNC milling method and 15.43-19.78 for the SLA method. Finally, the measured reflection coefficient values at 6 GHz are very close to the simulated reflection loss for both methods and therefore both two fabrication methods can be used in real applications. To briefly compare these two methods, the SLA method is more advantageous than the CNC milling method in terms of cost and low-weight. The CNC milling method is more resistant to heat and mechanical effects.

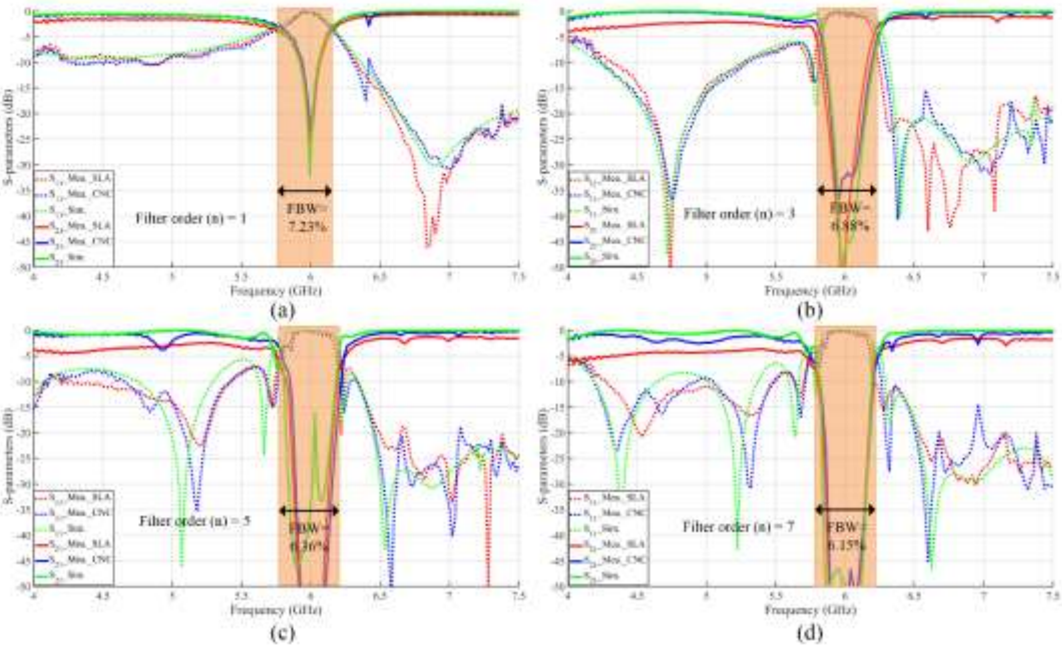

Fig. 2: The frequency responses of the proposed band-stop waveguide filters fabricated with CNC milling and SLA methods, (a) 1st order filter, (b) 3rd order filter, (c) 5th order filter, and (d) 7th order filter

Table 2. The performance comparison of the proposed band-stop waveguide filters

		f_0 (GHz)			$\|S_{11}\|_{max}$ (dB)			$\|S_{21}\|_{min}$ (dB)			FBW (%)			Q (f_0/BW_{3dB})		
		Simulation	Measurement (CNC)	Measurement (SLA)	Simulation	Measurement (CNC)	Measurement (SLA)	Simulation	Measurement (CNC)	Measurement (SLA)	Simulation	Measurement (CNC)	Measurement (SLA)	Simulation	Measurement (CNC)	Measurement (SLA)
Filter order	n=1	5.95	5.98	5.97	-0.18	-0.44	-0.33	-31.93	-24.00	-25.95	7.23	5.23	5.06	13.83	19.11	19.78
	n=2	6.00	6.02	5.99	-0.19	-0.33	-0.26	-62.12	-39.56	-38.48	8.15	6.68	6.48	12.26	14.97	15.43
	n=3	6.05	6.03	6.00	-0.21	-0.36	-0.22	-53.60	-47.01	-59.99	6.88	6.11	5.88	14.53	16.37	17.00
	n=4	6.01	6.03	6.00	-0.19	-0.42	-0.24	-79.89	-62.11	-65.32	6.57	5.68	5.58	15.22	17.59	17.92
	n=5	6.00	6.03	6.01	-0.20	-0.42	-0.22	-46.02	-67.73	-74.19	6.36	5.49	5.41	15.71	18.23	18.48
	n=6	5.97	6.03	5.99	-0.18	-0.41	-0.18	-50.95	-85.58	-64.09	7.39	5.32	5.79	13.53	18.78	17.27
	n=7	6.00	6.03	6.00	-0.19	-0.40	-0.22	-59.86	-65.64	-60.27	6.15	5.31	5.70	16.25	18.84	17.54

4 Conclusion

In this study, a band-stop WGF for C-band applications is designed, fabricated, and measured using SRR meta-resonators. The same filter is manufactured using CNC milling and SLA methods, which is one of the 3D printing methods, and the effect of the fabrication methods on the filter performance is evaluated. SRR meta-resonator geometry with rectangular geometry providing narrow bandwidth is preferred in the design and fabrication. The structures at 1st, 3rd, 5th, and 7th filter orders are evaluated and it is observed that the filter order leads to an increase in selectivity in the frequency response. In all filter orders, the structure fabricated by CNC milling gives partially better results than the structure fabricated by SLA, which is thought to be due to the varnish used for protection on the metal coating used in the SLA technique and a small amount of EM leakage also plays a role in these losses. In addition, the structure produced by the SLA method is about 50% lighter in weight than the structure produced by the CNC milling method. This result is of considerable importance for some applications where weight is important. In conclusion, according to the results obtained from this study, the SLA fabrication method is experimentally demonstrated to be a good alternative to conventional fabrication methods such as CNC milling.

Acknowledgment:
This study is carried out within the scope of the projectnumbered 123E108 supported by TUBITAK (The Scientificand Technological Research Council of Türkiye). Also, the metal coating of the proposed structure is carried out using 'the infrastructure on conductive coating on plastic surfaces' developed by Sağlamtek Aerospace Defense and DGN Coating Doğan Mazlum. We would like to thank them for their support.

References:

[1] J. Y. Jin, X. Q. Lin, Y. Jiang, and Q. Xue, “A Novel Compact E-Plane Waveguide Filter with Multiple Transmission Zeroes,” *IEEE Transactions on Microwave Theory and Techniques*, Vol.63, No.10, 2015, pp. 3374–3380. doi: 10.1109/TMTT.2015.2462825.

[2] J. Y. Jin, X. Q. Lin, and Q. Xue, “A Novel Dual-Band Bandpass E-plane Filter Using Compact Resonators,” *IEEE Microwave and Wireless Components Letters*, Vol.26, No.7, pp. 484–486, 2016. doi: 10.1109/LMWC.2016.2574818.

[3] M. Bod and H. Hatefi Ardakani, “A Dual- Mode Waveguide Filter Based on Stereometamaterial CSRR Resonator,” *Microwave and Optical Technology Letters*, Vol.60, No.12, pp. 3003–3006, 2018. doi: 10.1002/mop.31409.

[4] J. Cho *et al.*, “Effective Size Reduction of the Metallic Waveguide Bandpass Filter with Metamaterial Resonators and Its 3D-Printed Version,” *Sensors*, Vol.23, No.3, pp. 1173, 2023. doi: 10.3390/s23031173.

[5] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, “Magnetism from Conductors and Enhanced Nonlinear Phenomena,” *IEEE Transactions on Microwave Theory and Techniques*, Vol.47, No.11, pp. 2075–2084, 1999. doi: 10.1109/22.798002.

[6] G. V. Eleftheriades, O. Siddiqui, and A. K. Iyer, “Transmission Line Models for Negative

Refractive Index Media and Associated Implementations without Excess Resonators," *IEEE Microwave and Wireless Components Letters*, Vol.13, No.2, pp. 51–53, 2003. doi: 10.1109/LMWC.2003.808719.

[7] T. Haq and S. Koziel, "New Complementary Resonator for Permittivity- and Thickness-Based Dielectric Characterization," *Sensors*, Vol.23, No.22, pp. 9138, 2023. doi: 10.3390/s23229138.

[8] Y. Wu, Q. Zeng, and Y. Shang, "A Low- Insert Loss and High- Return Loss Bandpass Filter Based on Cut- off Rectangular Waveguide for Satellite Communication Application," *International Journal of RF and Microwave Computer-Aided Engineering*, Vol.31, No.2, 2021. doi: 10.1002/mmce.22351.

[9] B. Urul, H. Doğan, I. B. BaşyiĞiT, and A. Genç, "A Novel Broadband Double-Ring Holed Wlement Metasurface Absorber to Suppress EMI from PCB Heatsinks," *Turkish Journal of Electrical Engineering and Computer Sciences*, Vol.30, No.6, pp. 2254–2267, 2022. doi: 10.55730/1300-0632.3937.

[10] M. AbuHussain and U. C. Hasar, "Design of X-Bandpass Waveguide Chebyshev Filter Based on CSRR Metamaterial for Telecommunication Systems," *Electronics*, Vol.9, No.1, pp. 101, 2020. doi: 10.3390/electronics9010101.

[11] A. Bage and S. Das, "Compact Triple-Band Waveguide Bandpass Filter Using Concentric Multiple Complementary Split Ring Resonators," *Journal of Circuits, Systems and Computers*, Vol.26, No.06, p. 1750096, 2017. doi: 10.1142/S0218126617500967.

[12] A. Bage, "E-Plane Dual Band Bandstop Waveguide Filter for Possible X-band Applications," *International Journal of Electronics Letters*, Vol.12, No.3, pp. 295–303, 2024. doi: 10.1080/21681724.2023.2291809.

[13] A. Genç, B. Başyigit, T. Göksu, and S. Helhel, "Farkli Güç Oranlari için Dikdörtgen Dalga Kilavuzu Güç Bölücülerinin Karakteristiklerinin İncelenmesi," *Çukurova Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi*, Vol.33, No.1, pp. 261–270, 2018. doi: 10.21605/cukurovaummfd.420745.

[14] A. Genc, T. Goksu, and S. Helhel, "Fabrication of three- dimensional printed rectangular waveguide T- junction with in- phase and equal power division," *Micro & Optical Tech Letters*, Vol.60, No.8, pp. 2043–2048, 2018. doi: 10.1002/mop.31294.

[15] A. Genç, T. Göksu, and S. Helhel, "3D baski ve bakir kaplama ile üretilen dalga kilavuzu dönüş elemanlarinin performanslarinin incelenmesi," *Gazi Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi*, Vol.2018, No.2018, 2018. doi: 10.17341/gazimmfd.416538.

[16] P. Vaitukaitis, K. Nai, and J. Hong, "A Versatile 3-D Printable Model for Implementing Multiband Waveguide Filters With Flexible Filtering Characteristics," *IEEE Access*, Vol.11, pp. 110051–110059, 2023, doi: 10.1109/ACCESS.2023.3322364.

[17] K. Y. Chan, R. Ramer, and R. Sorrentino, "Low-Cost Ku-Band Waveguide Devices Using 3-D Printing and Liquid Metal Filling," *IEEE Transactions on Microwave Theory and Techniques*, Vol.66, No.9, pp. 3993–4001, 2018. doi: 10.1109/TMTT.2018.2851573.

[18] X. Shang *et al.*, "W -Band Waveguide Filters Fabricated by Laser Micromachining and 3-D Printing," *IEEE Transactions on Microwave Theory and Techniques,* Vol.64, No. 8, pp. 2572–2580, 2016. doi: 10.1109/TMTT.2016.2574839.

[19] A. Genc, I. B. Basyigit, T. Goksu and S. Helhel, "Investigation of the performances of X-Ku band 3D printing pyramidal horn antennas coated with the different metals," *2017 10th International Conference on Electrical and Electronics Engineering (ELECO)*, Bursa, Turkey, 2017, pp. 1012-1016.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)
The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself
No funding was received for conducting this study.

Conflict of Interest
The authors have no conflicts of interest to declare.