Investigation of the Performances of X-Ku Band 3D Printing Pyramidal Horn Antennas Coated with the Different Metals

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Abstract

In this study, X-Ku band 3D printed horn antennas coated with copper, chromium and nickel are designed and fabricated by means of fused deposition modelling (FDM) technique that is one of the additive manufacturing methods. Proposed fabrication method consists of two main steps that are to make the skeleton of horn antenna from acrylonitrile butadiene styrene (ABS) thermoplastic via 3D printer and to perform metal plating over the all surface of antenna by using the electroless plating and then electroplating processes. The simulation and measurement results for fabricated prototype of the copper-plated horn antenna are obtained in 10-15 GHz frequency, which is suitable for satellite communications. It is investigated the performances of these antennas in terms of the gain of antenna. These results confirm that the copper-plated horn antenna has the best performance in the three antennas due to having low relative permeability and high conductivity.

1. Introduction

Horn antenna has been one of the most common types of antennas in the fields of satellite communication, defense industry, radar etc. due to high directivity and wide bandwidth, its simplicity, ease of production and high efficiency [1]. It can also be used as a standard measurement element for calibrations and as a feeding element for dish reflector antennas in satellite systems [2, 3].

In recent years, there has been a growing interest for additive manufacturing (AM) in the production of high performance and monolithic microwave passive components with production time and cost competitiveness [4, 5]. The production of pyramidal horn antennas with FDM (fused deposition modelling) technique is a good alternative to traditional methods in terms of reduced weight, flexible applicability and monolithic. In conventional methods, microwave passive components are generally made of some metals via CNC machines, which is quite costly and complicated geometries are more difficult to fabricate [6].

Proposed fabrication method consists of two main steps that are to make the skeleton of horn antenna from ABS (Acrylonitrile Butadiene Styrene) thermoplastic via 3D printer and to perform metal plating over the all surface of antenna. The components of hollow and complicated geometry can be easily produced with this method. The critical parameters for better performance are high precision and low surface roughness especially at high frequencies. With the enhancement of 3D printing technology in the coming years, the components produced by this method can compete with commercial products in terms of performance. In this way, it is easy to produce many passive microwave components from the coupler to the filter. In this study, three 3D printing horn antennas coated with copper, nickel and chromium are manufactured. The impact of the metal type for horn antenna on the antenna gain was investigated.

Paper is organized as follows: Section 2 gives the design and fabrication of 3D printing pyramidal horn antennas at X-Ku band. Section 3 includes the simulation and the measurement results of the printed horn antenna coated with copper and also the impact of the type of metal on the antenna gain. Section 4 also contains the comparison and conclusion of results.

2. Design and Fabrication of 3D Printing Pyramidal Horn Antennas

The calculation of dimensions of pyramidal horn antennas is made for 12 GHz operating frequency at the X-Ku band (10-15 GHz), which is suitable for satellite communications. WR-75 rectangular waveguide is selected, the internal dimensions of which are 19.05 mm and 9.52 mm. The cut-off frequency is 7.86 GHz for TE10 mode. The dimensions of the antenna are calculated to provide a gain of 17 dB at the operating frequency. All calculations for dimensions of the antenna are made with an interface of Matlab GUI by using some formulations of [1, 7-9] references, comparatively. The internal aperture size of the antenna and the distance between the rectangular waveguide and the antenna's aperture are 70.91 x 49.07 mm and 70 mm, respectively. PE9819 coaxial-waveguide adaptor is used as the feeding. UDR 120 flange is selected for compatibility with the adaptor. The antenna thickness is decided to be 2 mm to be physically more robust. The photos of fabricated pyramidal horn antenna for all three phases are shown in Fig.1.

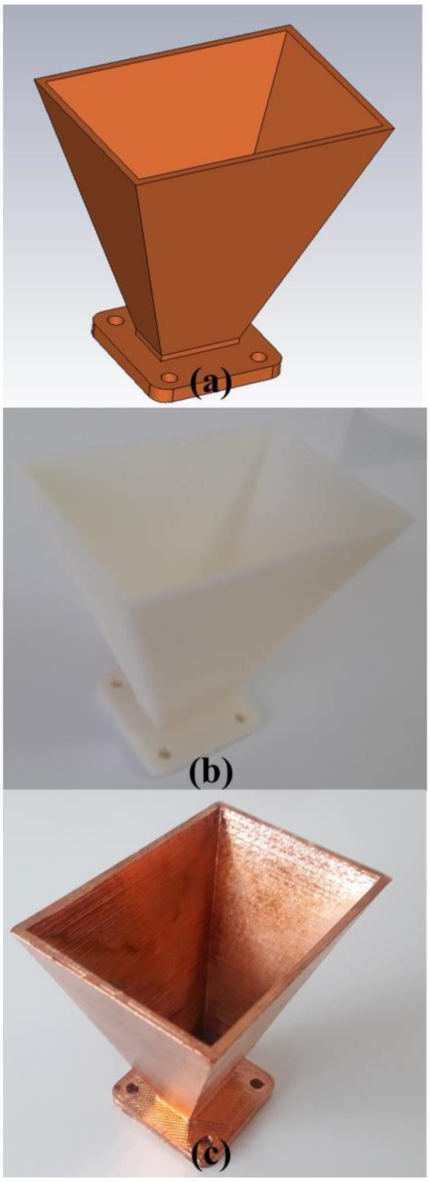

Fig. 1. Fabricated pyramidal horn antenna (a) CAD CST-model (b) ABS plastic after FDM fabrication (c) Copper-plated final shape

2.1. Printing the Antenna from ABS Thermoplastic

After the antenna dimensions were determined, CAD drawings were made with the CST Studio Suite® simulation program. STL extension file of CAD-model is obtained from CST and the G-code file is created by using the Repetier-Host program to be compatible with the 3D printer. Zortrax M200 model 3D printer working with FDM technique is used. White ABS thermoplastic is used as material for the 3D printer and the melting temperature of the plastic is 245 °C and also the fill rate is 80%. In addition, many parameters such as creating the support for cavities, layer height, first layers' number, shell thickness, working speed and type of pattern must be set before the printing. After printing from the 3D printer, the supports are dismantled and sanding is applied to reduce surface roughness.

2.2. Metal Plating of the Printed Horn Antenna

Since polymer materials such as ABS do not have electrical conductivity, the electroless plating and then electroplating methods are used to make the surface of the printed parts conductive. Electroless plating does not require an external electrical current contrary to electroplating. There is a limitation of electroless plating that its process is slower than electroplating. The advantage of this method is that it has a freedom in metal plating in all kinds of complex geometries [10].

The process of metal plating on ABS thermoplastic consists of the following steps that are etching, Pd-Sn activation, acceleration, electroless nickel, acidic copper plating, nickel plating and chromium plating, as shown in Fig. 2.

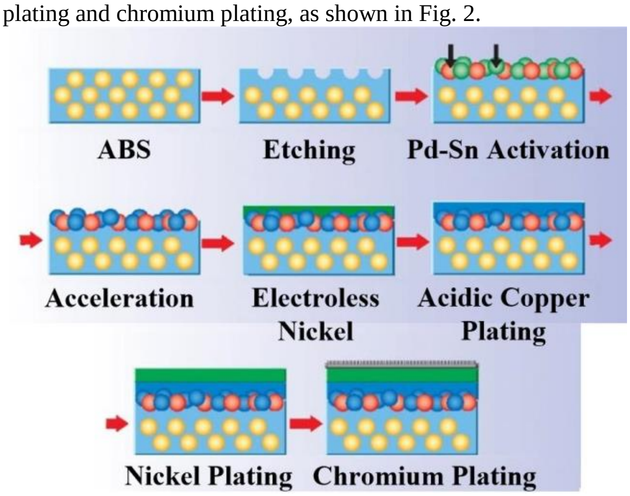

Fig. 2. Process of metal plating on ABS thermoplastic

First of all, ABS plastic is placed in the pre-erosion baths containing chromic acid and sulfuric acid to break the butadiene bonds. Pd-Sn activation is performed to place the tin (Sn^{+2}) and palladium (Pd^{2+}) ions in the broken butadiene bonds. Then, the accelerator is performed to remove excess palladium and tin on the surface of the part and electroless nickel plating process is applied. After this process, mat nickel plating consisting of a mixture of nickel chloride, nickel sulfate, boric acid is employed to strengthen the thin layer coating on the surface. Finally, all of process is completed by acid copper plating process involving copper sulphate ($CuSO_4$) and sulfuric acid (H_2SO_4).

The layer thickness with the electroless plating is limited to 3-4 μm. After the surfaces of the printed parts are conductive; thanks to copper, the multi-layer coating such as chromium and nickel plating can be applied over the copper layer till 20 μm which is thicker than skin depth at X-Ku frequency band. For example, the skin depth of copper at 10 GHz is about 0.66 μm. In this study, copper, nickel and chromium plating processes on the surfaces of three identical horn antennas are applied to compare the gain values of each antenna.

3. Simulation and Measurement Results of the Printed Horn Antenna Coated with Copper

All simulations are done in the Design Studio module of the CST Studio Suite® simulation program based on Finite Integration Technique (FIT). For the simulation, the accuracy of energy convergence is 100 dB, mesh per wavelength is 20, and mesh shape is hexahedral. Number of mesh cells is 3,307,100. All simulations were carried out on a personal computer using an Intel Core i7 2.60 GHz processor with 16 GB RAM and 128 GB SSD. Lossy copper (copper, annealed) is used as a metal. The open (add space) option is selected for the boundary condition in all direction and a waveguide port is used as the feeding.

The antenna measurement setup is given in Fig. 3. An E8363B Agilent PNA Microwave vector network analyzer (VNA) and PE9819 coaxial-waveguide adaptor is used for the measurements. Also, a SH2000-072 model double-ridged horn antenna is used as the reference antenna. The distance between the antennas is 110 cm. It is designed as a receiver antenna. However, it can also be used as a transmitting antenna at the same time due to the reciprocity principle. Radiation pattern and return loss of horn antenna coated with only copper is presented because the performances of three are approximately close except for the gain values.

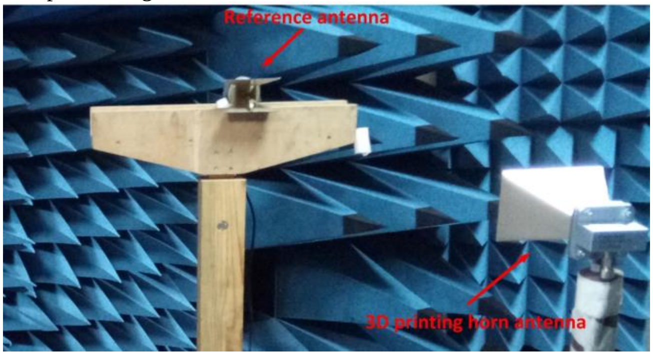

Fig. 3. Process of metal plating on ABS thermoplastic

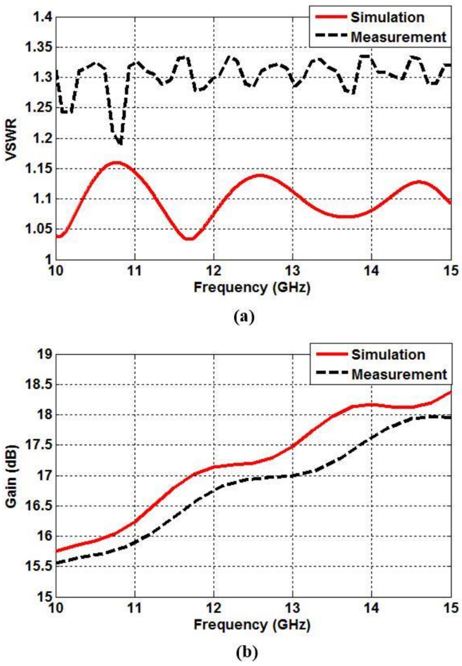

Fig. 4. (a) VSWR and (b) gain of the pyramidal horn antenna

VSWR and gain of the pyramidal horn antenna coated with copper is given in Fig. 4. VSWR of the antenna is quite good, as it is observed to be around 1.35. There is a certain difference between the measurement and the simulation results due to the surface roughness and dimensional tolerance of the antenna [11]. As the frequency increases, the gain of the antenna increases. The gain values vary from 16-18 dB and there is a 0.5 dB difference between the measurement and the simulation. E-plane (Ø=90^{o}) radiation pattern of the horn antenna in polar coordinates is given in Fig. 5. The main lobe is in the +z axis direction and the gain is 17.1 dB at 12 GHz. The side lobe level is -13.3 dB and the 3 dB beamwidth is 25.7^{o}. The side lobe level in H-plane is lower than in E-plane.

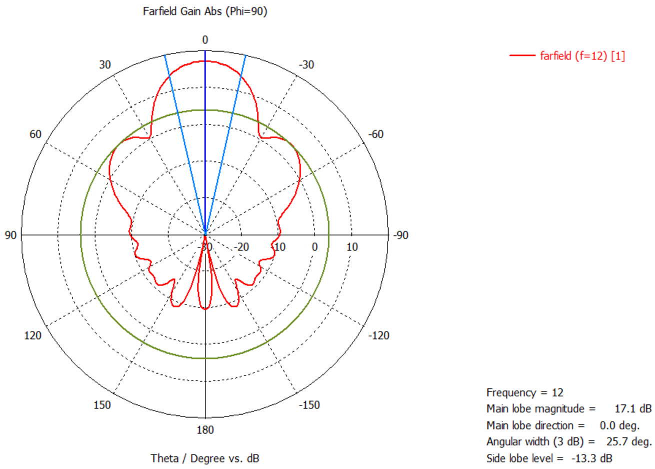

Fig. 5. E-plane radiation pattern of horn antenna in polar coordinates

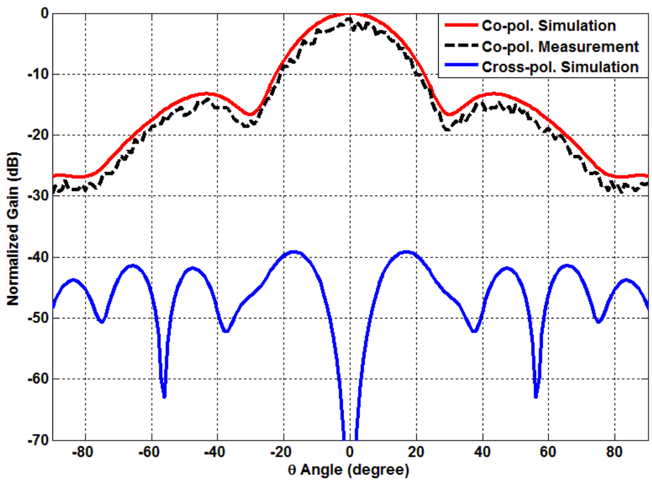

Fig. 6. E-plane radiation patterns of the 3D printed pyramidal horn antenna at 12 GHz

E-plane radiation patterns of the 3D printed pyramidal horn antenna at 12 GHz are given in Fig. 6. The level of cross-polarization in the normalized gain axis is less than -40 dB in the all frequency range. There is a good agreement between simulation and measurement results in terms of co-polarization that is defined as a component of the electric field in the same direction as the excitation polarization direction of an antenna.

The electric field component in the y direction of the electromagnetic wave traveling in the +z direction is co-polarization for the designed horn antenna. Cross-polarization is the electric field component, which is perpendicular to both the propagation direction of the EM wave and the direction of co-polarization. Here, the directions of co-polarization and the cross polarization are in the +y and +x directions. The goal in antenna design is to maximize co-polarization while minimizing cross-polarization.

4. The Impact of Metal Type of the Printed Horn Antenna on the Antenna Gain

Profile photos of 3D printing horn antennas coated with copper, chromium and nickel are given in Fig. 7. The conductivities (**σ**) of three lossy metals are 5.8 x 10^7, 1.44 x 10^7, 0.8 x 10^7, (S/m), respectively and also the relative permeabilities (**μ_r**) of three lossy metals are 1, 1 and 600, respectively. As seen, copper has the highest conductivity and chromium has the lowest conductivity.

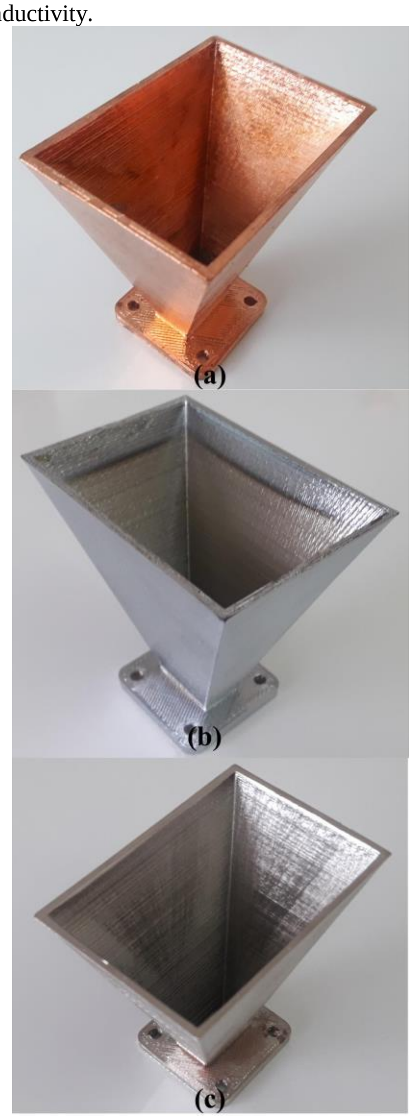

Fig. 7. Profile photos of 3D printing horn antennas coated with (a) copper (b) chromium and (c) nickel

Comparison of the gains of 3D printing horn antennas coated with copper, chromium and nickel is given in Fig. 8. Accordingly, the gain of the horn antenna coated with copper with higher conductivity is higher than the antenna coated with chromium while the relative permeabilities of these two antennas are equal. As expected, a high surface resistance gain reduces the slightly. In addition, though nickel conductivity is higher than chromium, the gain of the horn antenna coated with the nickel is lower because of that it has a higher relative permeability. The permeability constant affects both the skin depth and the current density that occurs at the surface. Therefore, a metal having low relative permeability and high conductivity should be selected for a better antenna performance.

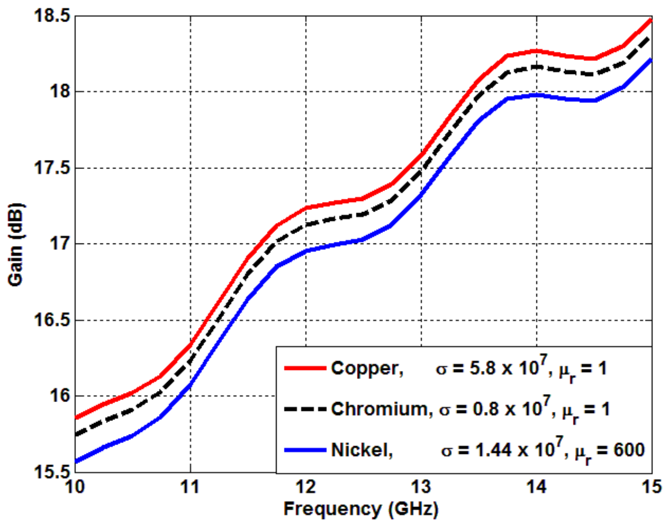

Fig. 8. Comparison of the gains of 3D printing horn antennas coated with copper, chromium and nickel

5. Conclusions

Three 3D printed horn antennas coated with copper, chromium and nickel are fabricated as an alternative to traditional methods in terms of reduced weight and low cost. The simulation and measurement results of the antennas are obtained in 10-15 GHz frequency band. It is observed that the copper-plated horn antenna has the best performance in the three antennas due to having low relative permeability and high conductivity. After the copper, the chromium-plated horn antenna should be preferred to the nickel-plated horn antenna due to having low relative permeability. The gain of the copper-plated antenna is 0.3 dB higher than the nickel-plated one.

6. Acknowledgment

This work was supported by The Department of Scientific Research Projects in Süleyman Demirel University named as ‘*Design of Ku Band Horn Array Antenna for Satellite Systems*’ and in Turkish “*Uydu Sistemleri için Ku bandı Huni Dizi Anten Tasarımı*” [Project Number: 4605-D2-16]. We also would like to thank Akdeniz University EMUMAM directorate (Grant Number: 2007K120530-DPT).

7. References

[1] C. A. Balanis, "Antenna theory: Analysis and design", vol. 1: John Wiley & Sons, 2005.

[2] T. S. Bird, "Fundamentals of Aperture Antennas and Arrays: From theory to design, fabrication and testing", John Wiley & Sons, 2016.

[3] M. Long and B. Blake, "Antennas: Fundamentals, design, measurement", The Institution of Engineering and Technology, 2009.

[4] P. T. Timbie, J. Grade, D. v. d. Weide, B. Maffei, and G. Pisano, "Stereolithographed MM-wave corrugated horn antennas", International Conference on Infrared, Millimeter, and Terahertz Waves, pp. 1-3, 2011.

[5] A. I. Dimitriadis, M. Favre, M. Billod, J. P. Ansermet, and E. d. Rijk, "Design and fabrication of a lightweight additive-manufactured Ka-band horn antenna array," 10th European Conference on Antennas and Propagation (EuCAP), pp. 1-4, 2016.

[6] I. Gibson, D. Rosen, and B. Stucker, "Additive manufacturing technologies rapid prototyping to direct digital manufacturing", Springer, 2010.

[7] K. T. Selvan, "Accurate design method for optimum gain pyramidal horns", Electronics Letters, vol. 35, pp. 249-250, 1999.

[8] K. Güney, "Improved design method for optimum gain pyramidal horns", International Journal of RF and Microwave Computer-Aided Engineering, vol. 11, pp. 188-193, 2001.

[9] K. Güney, "A new design method for optimum gain pyramidal horns", Electromagnetics, vol. 21, pp. 497-505, 2001.

[10] E. G. Geterud, P. Bergmark, and J. Yang, "Lightweight waveguide and antenna components using plating on plastics", 2013 7th European Conference on Antennas and Propagation (EuCAP), pp. 1812-1815, 2013.

[11] C. Garcia, R. Rumpf, H. Tsang, and J. Barton, "Effects of extreme surface roughness on 3D printed horn antenna", Electronics Letters, vol. 49, pp. 734-736, 2013.