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Implementation of a Lightweight and Portable Horn Antenna Using 3D Printing Technology

Serhan Yamacli[1,*]

[1] Department of Electrical-Electronics Engineering, Faculty of Engineering, Nuh Naci Yazgan University, Kayseri, Türkiye

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Abstract − In this study, a horn antenna operating at 5.8GHz centre frequency, which is an ISM operating frequency, is designed and manufactured. The novelty of the antenna is that it is produced using a 3D printer with a conductive filament containing carbon nanotube particles. The geometric dimensions of the antenna were calculated by means of an antenna design software. Then, the size of the radiating element of the antenna was optimized to set the centre frequency to 5.8GHz. It has been verified by electromagnetic simulations that the proposed antenna exhibits this centre frequency. Then, the antenna geometry was sketched in a 3-dimensional drawing program and made ready for printing. This antenna was fabricated on an Ultimaker 3D printer with a PLA filament con-taining conductive carbon nanotubes. The radiation element of the antenna and the SMA connector were finally attached to the printed antenna. The frequency response of the antenna is then measured using a vector network analyser and it has been shown that the produced pyramidal horn antenna works in the desired frequency band. The printed antenna has the desired frequency characteristic without the need for any additional coating or conductive spray thanks to the PLA filament containing conductive carbon nanotubes. The produced antenna has a weight of only 64.53 grams, including the SMA connector and the radiation element. The proposed lightweight and practical horn antenna design concept may have important applications considering the advances and needs of mobile defence and telecommunication systems.

Keywords *− Antenna design, 3-dimensional printing, conductive filament, electromagnetic simulation, horn antenna,*

1. Introduction

Antennas are used for the propagation and reception of electromagnetic waves in radio frequency (RF) systems. Electromagnetic wave propagation and reception are needed in many application areas such as telecommunications, defence and medical systems. Antennas with various parameters are needed for the propagation of high frequency signals in telecommunication systems, for the transition of the telecommunication signal from the transmitting system to the transmission medium and again from the transmission medium to the receiver system; in defence systems especially in radars that are used to determine position, speed and shape; and in medical systems where medical imaging signals are transmitted and received. In recent years, the demand for small and lightweight components is increasing especially in mobile telecommunication and defence systems. For instance, the use of mobile base stations in the form of drones in times of natural disasters are being implemented successfully (Bor-Yaliniz et al., 2018). Another contemporary example is mobile defence systems, and it is predicted that the use of these systems will increasingly continue (Hui et al., 2018). It is obvious that such applications will require components that are as small, compact and lightweight as possible. On the other hand, 3-dimensional (3D) printing methods are also being improved continuously and its application areas are widespread (Shahrubudin et al., 2019).

Apart from the engineering applications of 3D printing technology, their utilization areas are expanding to medical systems (Wang et al., 2019), drug delivery systems (Matthew et al., 2020) and many other areas (Phillips et al., 2020). In the engineering field, the application areas are expanding by diversifying the filaments, which are the raw materials of 3D printing (Hu et al., 2018).

[1] syamacli@nny.edu.tr
*Corresponding Author

Various antenna implementations employing 3D printing technique exist in the literature. For example, (Yao et al., 2017) proposed a horn antenna with a centre frequency of 28GHz and printed on a 3D printer using insulating filament. Then, copper-containing conductive spray paint and conductive tape were adhered to insulating plastic antennas, and the measurements were performed and then the performance of the antennas were compared for these two cases. Similarly, an antenna with a circular reflector operating in the microwave X-band was printed with a polylactic acid (PLA) filament, and its measurements were performed after painting it with conductive spray paint. This antenna has been concluded to operate properly at the centre frequency of 10GHz (Tak et al., 2017). In another study, a horn antenna was printed with PLA filament using a 3D printer to operate in the 14-18 GHz band, then electrochemical deposition technique was used for metallic coating (Kyovtorov et al. 2017). It has been shown by measurements that this antenna works properly in the planned frequency band. In another study, an antenna was implemented to operate in the microwave D-band and the performances of conductive coated polymer and direct metallic printing were compared (Gu et al., 2020). In (Esfahani et al., 2018), a capsule-shaped antenna is printed using a 3D printer with silver and copper plating, and this antenna has been shown to work as expected. In another study, a 2x1 horn antenna array structure was given and the entire structure, including the feeding elements, was implemented using a 3D printer with acrylonitrile butadiene styrene (ABS) filament; and then copper electroplating was applied on the structure (Genç, 2019). The measurements showed that the antenna worked as expected. In another study, the gains of horn antennas, which are implemented on a 3D printer using ABS filament, are experimentally investigated for the cases where they are coated with copper, chrome and nickel (Genç et al., 2017). On the other hand, a double-backed horn antenna was implemented in (Lee et al., 2018) to operate in the 6-18 GHz range, printed on a 3D printer, and its performance was measured after coating it with silver-containing conductive paint. It has been shown that this antenna also works as expected. In another study, a 16x16 dipole antenna array was printed on a 3D printer, coated using electrodeposition method and then the characteristics of this printed antenna and the equivalent antenna made of standard aluminium were compared (So et al., 2018). In (Zhang et al., 2018), horn antennas were produced as prototypes, copper alloy and aluminium alloy horn antennas were produced with metallic 3D printing technique and then performance tests were conducted. Although these types of metallic antennas outperform coated antennas, manufacturing costs are seen as a drawback. In (Kwon et al., 2017), fractal antennas were proposed, the insulating frame part was produced with 3D ABS filament, the conductive parts were made using copper strips, and then performance tests were carried out. In an paper reviewing the production of 3D high-frequency elements, it has been reported that elements produced with the metallic 3D writing technique have better thermal and physical stability than plastic elements that are subsequently painted with conductive paint (Zhang et al., 2017). Information about the antenna and other supporting RF components implemented with silver-containing paint and PLA printing was given by (Kiesel et al., 2020) and it was concluded that the silver paint was successful for providing adequate conductivity. A horn antenna design for ultra-wideband applications was demonstrated by (Midtboen et al., 2017). Another horn antenna operating in the microwave X-band (8-12GHz) is 3D printed using insulating ABS filament, then silver-containing conductive paint, copper-containing adhesive tape and copper plating processes are utilized to provide conductivity (Chuma et al. 2019). The performances of these antennas are compared and it was concluded that the performance of the horn antenna implemented with copper coating performs better than the others.

In this study, a horn antenna with a 5.8GHz centre frequency is designed and implemented using 3D printing technique. This centre frequency is selected to be used in Industrial, Scientific and Medical (ISM) applications (Mishra et al., 2019; Mazar, 2014). The antenna dimensions is firstly computed and optimized using antenna design and electromagnetic simulation tools. Then, the planned antenna geometry was laid out in the 3D modelling program and then printed with a 3D printer using a PLA filament containing conductive carbon nanotube particles. No other coating or deposition is applied to the implemented antenna. Then, a subminiature version A (SMA) connector is attached to the antenna and then calibrated measurements were performed using a vector network analyser (VNA) device. The measurements have shown that the antenna works as expected at the expected frequency range. Thus, it has been shown that 3D antennas can be implemented using carbon nanotube doped conductive PLA filament with accurate electromagnetic characteristics. The weight of the produced antenna is 64.53 grams, which it is much lighter than its metallic counterparts. It is concluded that the use of conductive carbon nanotube doped PLA filament for the implementation of 3D printed antennas can be deployed for the fast production of lightweight antennas in mobile defence and telecommunication systems.

2. Materials and Methods

2.1. The Design and Simulation of the Pyramidal Horn Antenna

In this study, a pyramidal horn antenna, which is a widely used antenna type, was designed and implemented. The model of a typical pyramidal horn antenna is given in Figure 1.

A typical pyramidal horn antenna consists of three sections as can be seen in Figure 1 (Balanis, 2016) The first section is the waveguide part shown in green, the second is the aperture section shown in blue, and the third is the radiation element shown inside the waveguide. Descriptions of the geometric parameters shown in Figure 1 are presented in Table 1. In this study, an antenna design that can be used in ISM systems is aimed. Therefore, the centre frequency of the antenna was chosen as f_c=5.8GHz. In addition, the input impedance is taken as the standard 50Ω reference level and the minimum gain is selected as 10dBi. These design parameters were entered to an antenna design software and the geometric dimensions of the antenna were obtained as in Table 1.

In order to test the proper functioning of the design before the manufacturing of the antenna, the antenna geometry was imported as shown in Figure 2a and simulated in an electromagnetic simulation software. In the simulation program, the frequency range is selected 5-7GHz, the iteration residual limit is –40dB, and the boundary conditions are chosen as space. After the simulations, the length of the radiation element was optimized as 14.02mm, and the S_{11} characteristic obtained according to this value is shown in Figure 3. As it can be seen from this simulation result, the proposed antenna operates in a wide band around the 5.8GHz centre frequency.

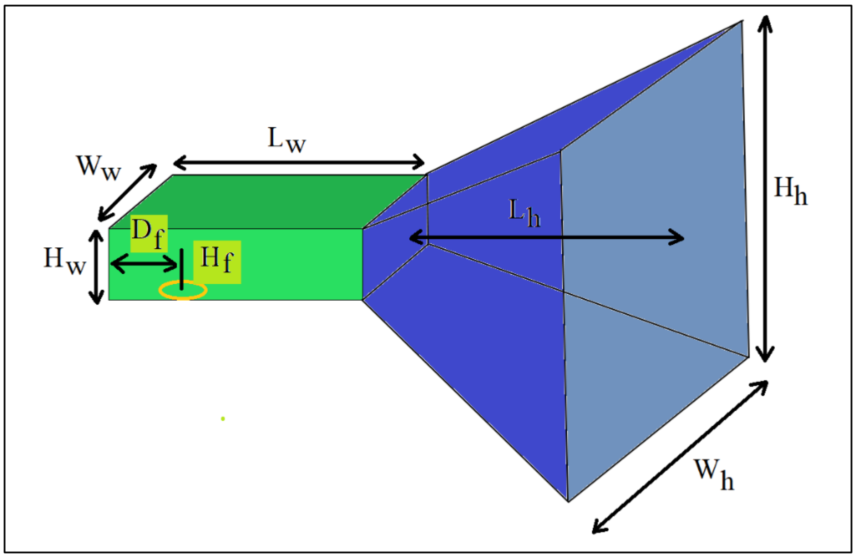

Figure 1. Pyramidal horn antenna model.

Table 1

Geometric parameters of the pyramidal horn antenna and the values for f_c=5.8GHz centre frequency.

Parameter shown in Figure 1	Explanation	Value obtained by the design software
H_w	Height of the waveguide section	19.91mm
W_w	Width of the waveguide section	39.81mm
L_w	Length of the waveguide section	50.86mm
H_h	Height of the aperture section	76.17mm
W_h	Width of the aperture section	105.27mm
L_h	Length of the aperture section	31.22mm
H_f	Length of the radiation element	14.47mm
D_f	Distance of the radiation element to the back surface of the antenna	9.56mm

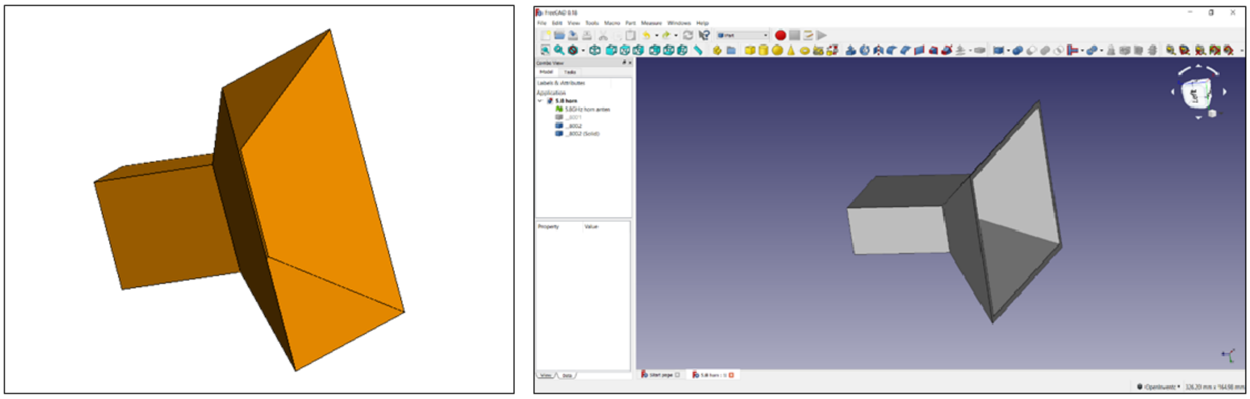

Figure 2. a) The view of the designed pyramidal horn antenna in the simulation software, b) FreeCad drawing of the 3D printing of pyramidal horn antenna.

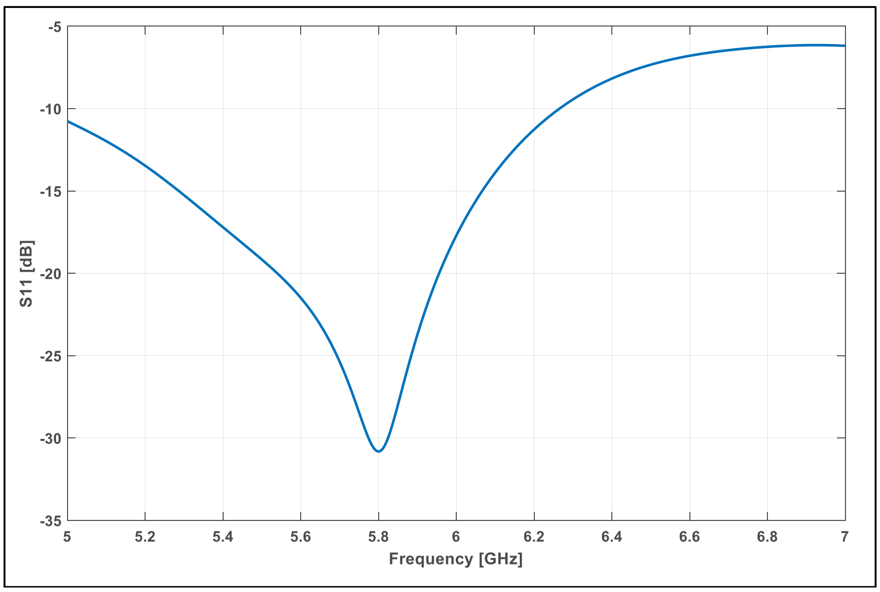

Figure 3. The S_{11} characteristic of the antenna obtained from electromagnetic simulations.

2.2. Manufacturing of the Designed Horn Antenna Using 3D Printing Technique

The pyramidal horn antenna, which was designed in the previous section and whose center frequency is fine-tuned with simulations, has been drawn in a way that can be printed in 3D. FreeCad software, a free program, was used for the 3D drawing process (FreeCad, 2021). The parametrically drawn antenna is shown in Figure 2b.

The 3D drawn antenna was printed on an Ultimaker 3D printer. The .stl file for the drawing was imported to the Ultimaker Cura software and the output was adjusted with 0.1mm layer thickness and 30% filling rate. Functionalized F-Electric® PLA filament, which has high conductivity, was used as the conductive filament. This filament can be used in applications that require high conductivity thanks to the included conductive carbon nanotube particles making it to have a volume resistivity of 0.75Ω.cm which corresponds to the volume conductivity of 1.33S/cm (Functionalize, 2021). In the 3D printed antenna geometry, the relevant holes were carefully drilled at the position of the radiation element and then the SMA type connector, on which the radiation element was soldered, was attached to the anten-na. No solder or conductive material is applied between the SMA connector and the antenna body. Photographs of the manufactured antenna are shown in Figure 4. 48.94 cm3 conductive PLA filament was used for the production of this antenna. The resulting antenna, including the SMA connector, is 64.53 grams and provides a significant weight advantage over its metallic counterparts (ETS, 2021; NS-MI, 2021; Pasternack, 2021) that is around 500~700 grams.

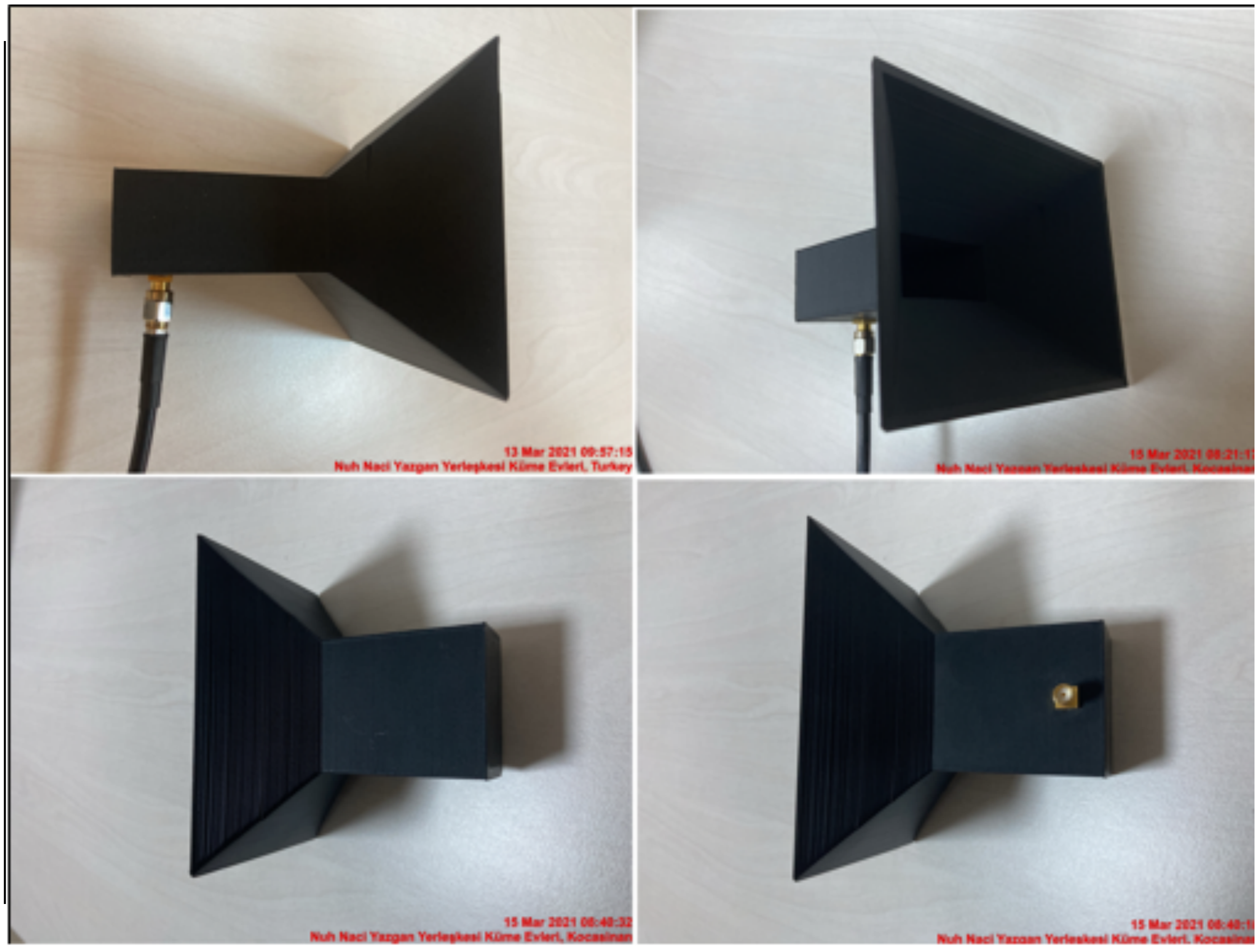

Figure 4. Images of the manufactured antenna.

3. Results and Discussion

A Rohde&Schwarz ZVH8 vector circuit analyser (VNA) was used to measure the manufactured pyramidal horn antenna. In order to increase the accuracy of the measurements, a 201-point calibration between 5-7GHz was performed with the ZV-Z135 SMA calibration kit before the measurements. The scattering parameters of the produced antenna were then measured as shown in Figure 5. During the measurements, the screenshot of the device was recorded as shown in Figure 6. In addition, the measurement data are saved and plotted in the MATLAB environment as shown in Figure 7.

According to the measurement results, the frequency range in which the antenna's reflection coefficient (S_{11}) is below the reference value of –10dB is between 5.22GHz and 6.55GHz, and the centre frequency value of the S_{11} is determined to be 5.79GHz at which the S_{11} has the lowest value of –40.52dB. From this point of view, it is seen that the measured centre frequency is very close to the targeted centre frequency of 5.8GHz. Moreover, it has been shown that the operating range of the produced antenna readily covers 5.725GHz-5.875GHz, which is the range of the ISM 5.8GHz band. Hence, the experimental results verify that the implemented antenna has the desired frequency characteristic without the need for any additional coating or conductive spray thanks to the utilization of the PLA filament containing conductive carbon nanotubes. Furthermore, the produced antenna including the SMA connector and the radiation element has the weight of only 64.53 grams, making it a feasible alternative for a variety of applications demanding lightweight antenna components.

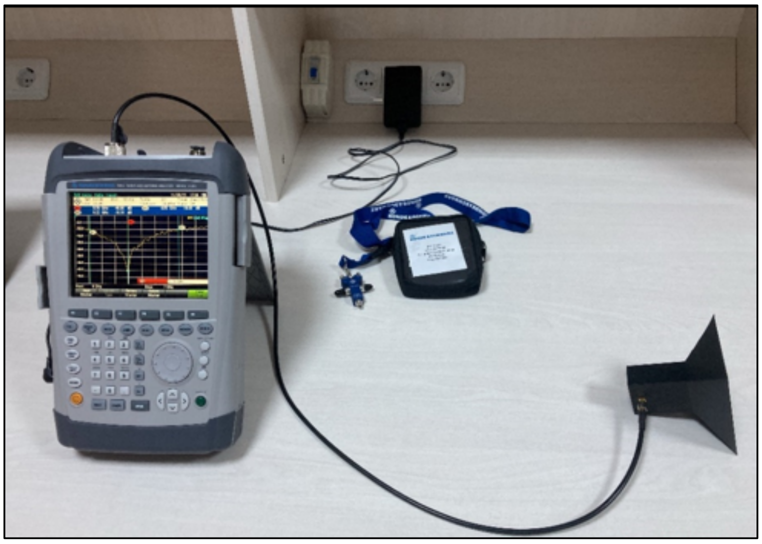

Figure 5. Experimental setup

Figure 6. The screenshot of the VNA screen during the measurement of the manufactured antenna

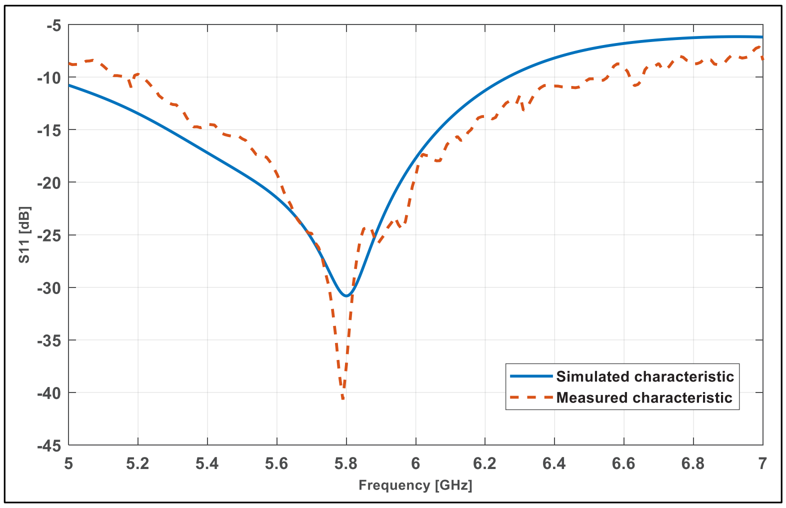

Figure 7. The measured and simulated S_{11} characteristics of the manufactured antenna

As the next step, the gain-frequency characteristic of the antenna is measured in anechoic chamber using the ZVH8 VNA. A Pasternack standard gain horn antenna is employed as the reference antenna which is placed at a distance of 1m from the 3D printed antenna. The obtained gain-frequency plot of the antenna is shown in Figure 8. As it can be seen from Figure 8, the measured antenna gain closely follows the simulated gain. The simulated antenna gain at the centre frequency of 5.8GHz has the value of 12.7025dB where the measured gain is 12.6341dB at the same frequency point.

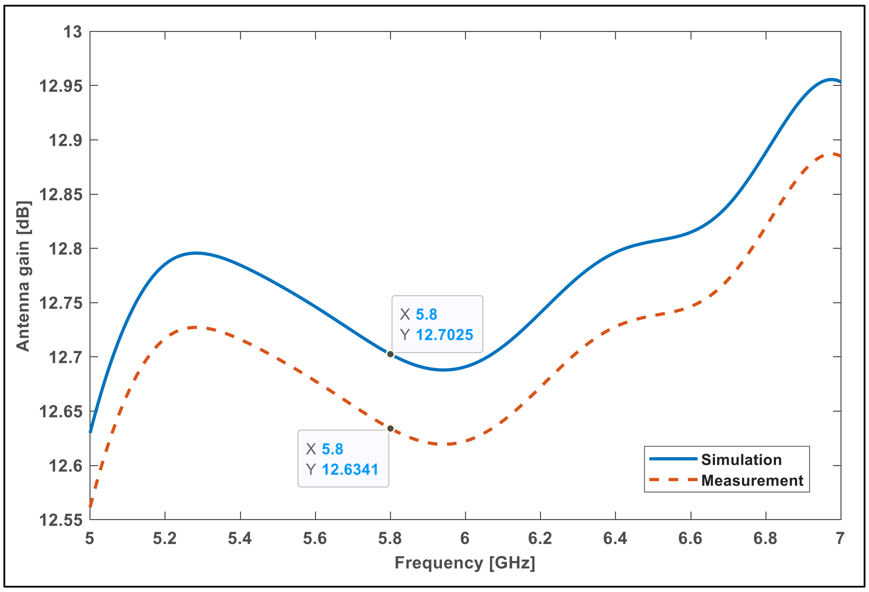

Figure 8. Gain-frequency characteristic of the manufactured antenna

The E-plane (φ=90°) farfield radiation pattern of the antenna is obtained in polar coordinates as given in Figure 9. From this figure, the antenna gain is confirmed as 12.7dB at 5.8GHz and the direction of the main lobe is in line with the +z axis. The 3dB beamwidth has the angle of 36.6° and the side lobe level has the value of -17.1dB.

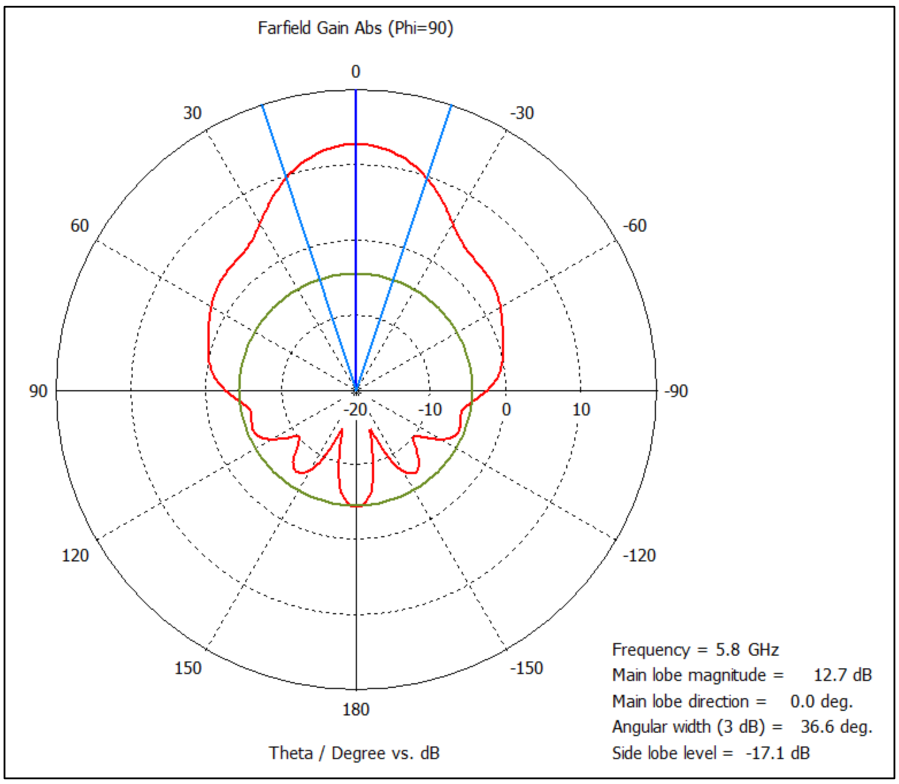

Figure 9. E-plane farfield radiation pattern of the antenna in polar coordinates

Finally, the normalized gain of the manufactured antenna is obtained and plotted as shown in Figure 10 for the centre frequency of 5.8GHz. It is seen from Figure 10 that the measured normalized gain of the antenna is close to the simulated case demonstrating the versatility of the filaments containing conductive carbon nanotube particles for use in 3D printing of antennas.

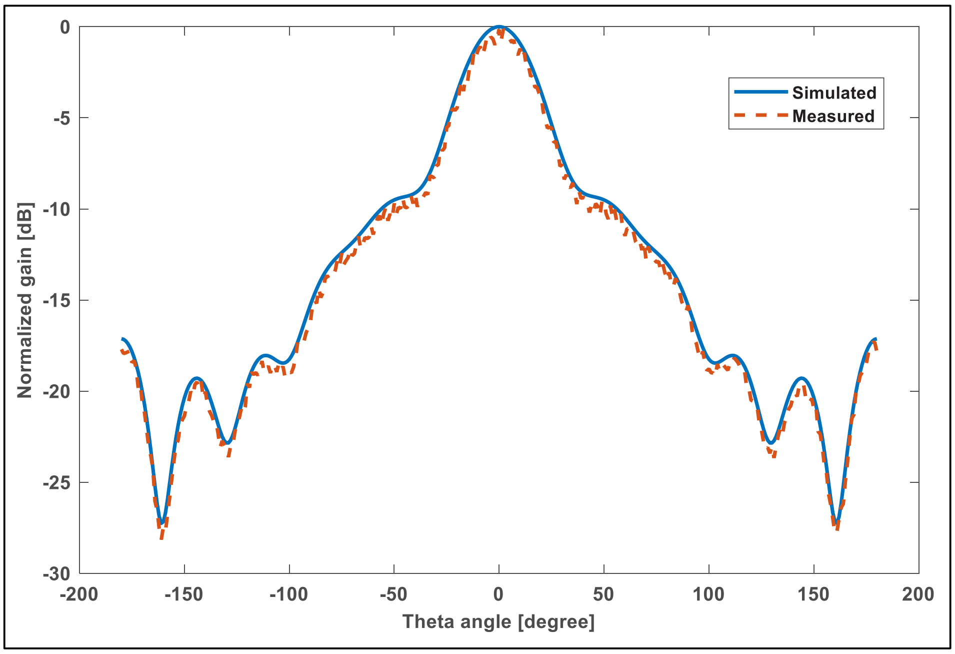

Figure 10. Normalized gain of the antenna at 5.8GHz centre frequency

4. Conclusion

In this study, a pyramidal horn antenna is designed and manufactured for the 5.8GHz ISM frequency band. First of all, the antenna dimensions were computed according to the required frequency band and then the size of the radiation element was optimized by simulating the antenna via an electromagnetic simulation software. As the next step, the proposed antenna was modelled on FreeCad, a 3D drawing program, according to the final geometric dimensions. The antenna geometry was manufactured on an Ultimaker 3D printer with a conductive PLA filament containing carbon nanotube particles. Then, the antenna production was completed by adding the SMA connector and the radiation element to the antenna. The calibrated Rohde & Schwarz ZVH8 VNA device was used for the measurement of the produced antenna. The measurement results show that the antenna operates in the 5.22GHz-6.55GHz range. The antenna provides a reflection coefficient lower than –20dB in the 5.725GHz-5.875GHz frequency range, which is the targeted 5.8GHz ISM band. Moreover, the gain-frequency characteristic and the farfield radiation pattern of the manufactured antenna are obtained and presented. The simulated and measured antenna gains are 12.7025dB and 12.6341dB, respectively, at the centre frequency of 5.8GHz. The normalized antenna gain with respect to the theta angle is also given, which shows that the characteristic of the 3D printed antenna closely follows the simulated values demonstrating the versatility of the filaments containing conductive carbon nanotube particles for the manufacturing of 3D printed antennas. Therefore, it has been concluded that the designed and manufactured pyramidal horn antenna works as expected. As a result, it has been shown that conductive filaments containing carbon nanotube particles can be used in 3D antenna production and the antennas manufactured in this way possess a weight advantage thus their use in mobile defence and telecommunication systems can be advantageous.

Conflicts of Interest

The authors declare no conflict of interest.

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