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Design of a 3D Printed UWB Antenna for a Low-Cost Wireless Heart and Respiration Rate Monitoring

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Abstract. This paper introduces an ultra-wideband (UWB) horn antenna for a low-cost wireless heart and respiration rate monitoring that is manufactured by a 3D printing technology. The proposed design operates within 3.1-10.6 GHz. The horn antenna is designed within the 15-dB gain which is sufficient to be used in medical system. The horn was designed to calculate the gain in MATLAB using an approximation method and simulated using CST Microwave Studio. The proposed antenna is 4-6 GHz (G-Band) operating. A printed antenna which is supported by WR-187 rectangular waveguide is fabricated using low cost polylactic acid (PLA). The surface is then metalized using copper tape on the inside. The simulation result of reflection coefficient for different conductivity and thickness of coating metal is compared, the developed 3D printed antenna successfully operated within given frequency range of 3-11 GHz which covered the ultra-wideband frequency range.

1. Introduction

Ultra-wideband (UWB) antenna contains a lot of potential applications to be investigated. Some of the area of research is in medicine. UWB antennas are non-invasive, consumes low power and has portable form factor [1]. This makes it ideal for vital signs monitoring. In 1994, McEwan licensed the first UWB for remote detection at the Lawrence Livermore National Laboratory [2]. It is possible to connect the built antenna for comfortable patient inspection, for injured persons, where no detector can be connected to the body or for house observation systems [3]. Thus, an ultra-wideband (UWB) antenna frequency for heart and respiration rate system application are between 3.1-10.6 GHz.

Tracking of individuals respiratory condition without touch becomes a useful tool in sleep monitoring and home health care applications. Current fixed-electrode electrocardiogram (ECG) disturbs clinicians with conditions such as children at risk of sudden infant syndrome, adults with sleep disorientation or fire victims.

In 2002, the U.S. Federal Communications Commission (FCC) allowed the unpermitted use of 3.1-10.6 GHz for UWB to regulate the use of UWB technology [4]. FCC has slowly allowed these bandwidths to be used commercially, making it possible for all common people to benefit from the features of UWB.

For low-cost fabrication, 3D printing was a great technology to produce a horn antenna. Three-dimensional printing is a new technology allowing artifacts to be produced directly from the digital model design. Over the past few years, 3D printing has been utilized for the fabrication of antennas. A 3D printing provides low cost and high efficiency advantages compared to the traditional digital CNC process.

Throughout this paper, simulation and measured result of the printed antenna is presented using FDM 3D printing technique. The paper is organized as follows. In Section 2, the previous studies were discussed. Section 3 explained on the designing method of the pyramidal horn antenna using approximation method by including the design simulation for conductivity and thickness of the coating metal. Section 4 contains the simulations and measurement result and fabrication of horn antenna. Comparison is made between measurement and simulation result. Finally, in Section 5 conclusions of results and the future work are presented.

2. Previous study

There are a variety of common types of wideband antennas such as microstrip, monopole and horn antennas. Throughout previous research, the approximation approach is widely used by a model of the ultra-wideband horn antenna that is used in the designed medical imaging device. A 15-dB gain approximation value is used. Using rectangular wave-guide C band supporting that frequency, the frequency used is 7 GHz [5].

3D printed production methods are now very famous in the research because of their ability. 3D printing is also very promising when it comes to passive component design, because the production process will be much faster, easier and more cost-effective.

The impact of the metal type for horn antenna on the antenna gain was investigated in [6]. 3D printing pyramidal horn antennas at X-Ku band were designed and fabricated. Results of the copper-coated printed antenna were observed as well as the effect of the metal type on the antenna. The 3D printing horn antennas coated with copper (Cu), chromium (Cr) and nickel (Ni).

Information from the chosen papers is summarized in Table 1. Table 1 and also presented the material of the 3D printing and the coating material used by the previous researcher. From the table, common materials that are used for 3D printing are polylactic acid (PLA) and Acrylonitrile Butadiene Styrene (ABS). However, PLA and copper are mostly used among the researchers as the material for 3D printing and coating metal respectively.

Table 1. An overview of 3D printing material for antenna by previous researcher.

Ref	Type of horn antenna	Frequency (GHz)	Material	Coating
[6]	Pyramidal	12	ABS	Cu, Cr and Ni
[7]	Pyramidal	10–15	ABS	Cu
[8]	Pyramidal	8.2-12.4	PLA	-
[9]	Monopole	3.5	PLA	Cu clad
[10]	Double Ridge	2.4-5.1	PLA	Silver Cu spray paint
[11]	Pyramidal	28	ABS	Cu tape and conductive Cu paint

3. Antenna design

3.1. Design of horn aperture

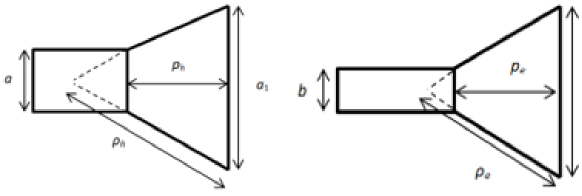
The fundamental design is based on the pyramidal horn antenna are showed in Figure 1. The dimension of the waveguide, center frequency and antenna gain are the main factors that will determine the dimension of horn antenna [12]. In this work, we use the basic design of 15 dB pyramidal horn antenna having non-curved flare. The purpose is to decide the remaining dimensions which are a_1, b_1, ρ_e and ρ_h. In this paper, the waveguide is selected by the mid frequency 5 GHz. The inner dimension a and b is chosen to be 47.55 x 22.15 mm respectively which is closer to WR-187 that support the frequency 3.95-5.85 GHz (G-Band).The dimension of the antenna is estimated using the approximation method [4] as

$$G_0 = \frac{1}{2}\frac{4\pi}{\lambda^2}(a_1 b_1) = \frac{2\pi}{\lambda^2}\sqrt{3\lambda\rho_h}\sqrt{2\lambda\rho_e} \tag{1}$$

where, λ is the wavelength of center frequency and G_0 is the desired gain (dimensionless). Then by utilizing below equation (2) and (3), p_e and p_h can be determined.

$$p_e = (b_1 - b)\left[\left(\frac{\rho_e}{b_1}\right)^2 - \frac{1}{4}\right]^{\frac{1}{2}} \tag{2}$$

$$p_h = (a_1 - a)\left[\left(\frac{\rho_e}{a_1}\right) - \frac{1}{4}\right]^{\frac{1}{2}} \tag{3}$$



(a) (b)

Figure 1. Horn antenna structure a) H-plane view (b) E-plane view.

All calculations are carried out via MATLAB GUI. Table 2 shows the parameter of the design antenna for 15dB gain.

Table 2. Parameters of design antenna for 15 dB gain.

Parameter	Value (mm)
a	47.55
b	22.15
a_1	154.73
b_1	114.43
ρ_e	109.12
ρ_h	133.00
p_e	74.94

p_h	74.97

3.2. *Simulation of design antenna*

The antenna will be simulated through the CST program once the design is complete. All simulations were carried out on a personal computer using an AMD RADEON R4 2.60 GHz processor with 16 GB RAM and 128 GB SSD. The open (add space) option is selected for the boundary condition in all direction and a waveguide port is used as the feeding. Simulations about different conductivity and thickness of coating metal were carried out.

3.2.1. Conductivity and thickness of coating metal. The horn antenna was simulated under different conductivity of metallization which is copper, aluminium, zinc, tin and mercury. Table 3 shows the conductivity of different metal tested.

Table 3. Conductivity of metal [13].

Parameters	Value (mm)
Copper	5.980x107
Aluminium	3.500 x107
Zinc	1.682x107
Tin	8.700x106
Mercury	1.044x106

The conductivity of the metal was chosen from high conductivity to low conductivity. Based on Table 3, copper shows the highest conductivity of metal. Moreover, copper tape is the metal that usually use as the coating material for 3D printing. As for the thickness of the conductance material, the horn antenna was simulated under different thickness of copper which is 0.005 mm, 0.01 mm, 0.05 mm, 0.1 mm and 0.5 mm.

4. Results and Discussion

The frequency and return loss are parameters which are collected from the simulation process. The results shown below are the most significant result of the simulation that determines the strength of the transmitted signal through the horn antenna.

4.1. Simulation result for conductivity of coating metal

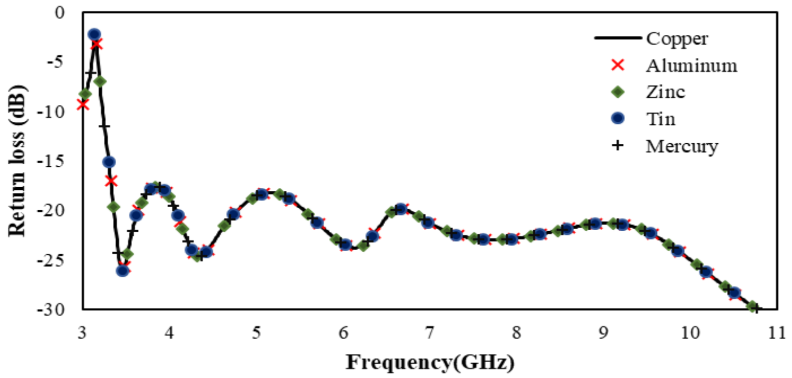


Figure 2. Simulated return loss antenna using different coating material.

Figure 2 shows the return loss for the simulated horn antennas that is coated with copper, aluminium, zinc, tin and mercury. The conductivities (σ) of five metals were given in Table 3. As observed, copper has the highest conductivity among all comparing to mercury that has the lowest conductivity. The return loss is below than -10 dB from 3.5-10 GHz. This meant that all of the material can be used as coating material because of the signal transmitted through the antenna had been received with minimum loss.

In previous work [6], researcher investigate the impact of metal type on the antenna gain. The 3D printing horn antennas coated with copper, chromium and nickel. It is observed that due to low relative permeability and high conductivity, the copper-plated horn antenna has the best performance between three antennas.

From the analysis, conductivity of the metal did not show any significant in the result obtained. Therefore, as for this work, copper is chosen as it is commonly utilized in the previous studies [7-11, 14]. Therefore, a metal having low relative permeability and high conductivity should be selected for a better antenna performance.

4.2. Simulation result for thickness of copper coating

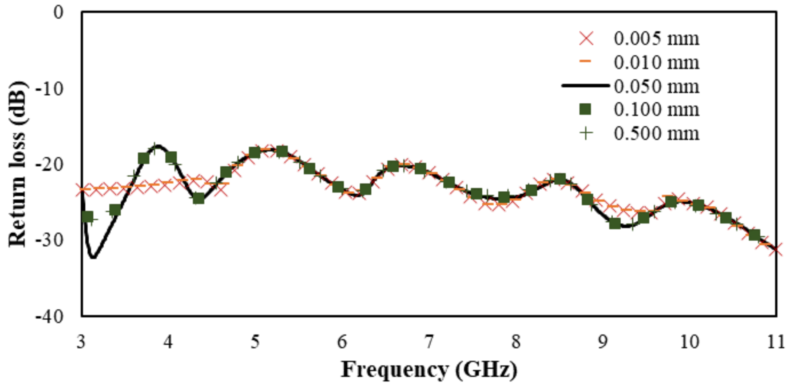


Figure 3. Simulated return loss antenna coated with copper using different thickness of copper material.

Figure 3 shows the comparison of return loss for different thickness of copper. The layer height is a very critical parameter for providing a smooth surface for metal coating. Return loss for different thickness used is below than -10 dB from 3-11 GHz frequency. Thickness of the copper is not affected by the copper material loss in comparison to the surface roughness. From Figure 3, it can be concluded that 0.05 mm is an acceptable thickness to be used for the fabricated horn. The copper tape is already compatible and available in the market. Therefore, additional layer of tape is unnecessary.

4.3. Horn antenna fabrication

The proposed manufacturing process consists of two major steps for making the main frame of the horn antenna from thermoplastic PLA (polylactic acid) via a 3D printer and to use the Cu tape to conduct metal coating on the antenna layer. One of the good points of using horn antennas with structures built in a 3D printer with PLA is the weight being lighter than the horn antennas built by the conventional process. The dielectric constant of PLA product is 2.72 and the loss tangent is 0.008. As shown in Figure 4 (a), the fabricated horn before coating while (b) was coated with Cu tape inside the square flange. The Cu tape is 0.05 mm thick.

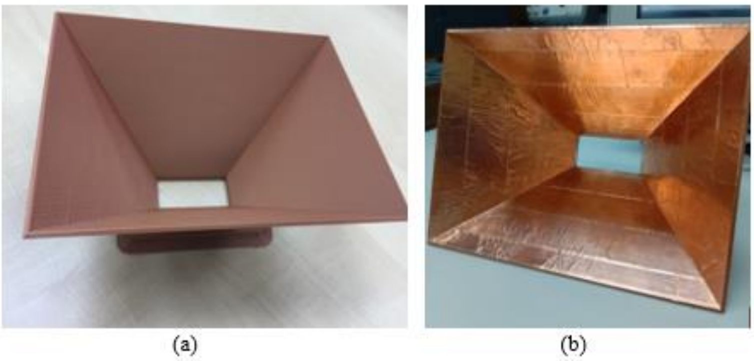


Figure 4. Fabricated 15 dB horn antenna. a) horn antenna without coating b) horn antenna after coating with 0.05 mm copper tape.

The adapter of the waveguide is WR-187, which operates from 3.95-5.95 GHz. The developed antennas were attached to a waveguide coaxial adapter using a vector network analyser (VNA) for measurement. A short –open-load calibration was established with experimental setup. As shown in Figure 5, the return loss magnitude for simulated and measured 15 dB horn antenna is lower than -10 dB from 3.5-7.0 GHz. The factors that caused the difference in measurement and simulation results are surface roughness, manufacturing tolerance and mismatch loss. The roughness of the surface is caused by the 3D printer's tolerance error. Another factor is mismatch loss which is due to the incompatibility of the coaxial-waveguide adapter flange with the antenna flare [15].

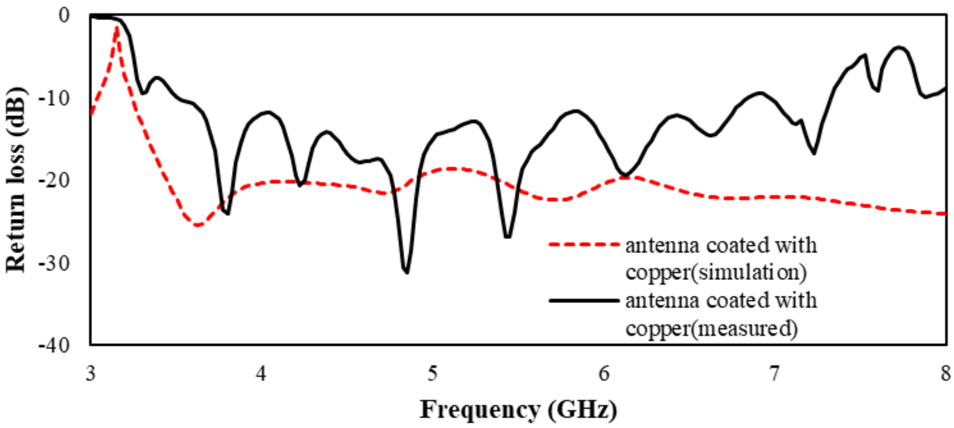


Figure 5. Comparison of measured and simulated return loss for antenna coated with copper.

4.4. Comparison to previous work

Table 4 shows the comparison of the proposed antenna design with the reported work. According to the [6], the gain of the coated copper antenna with higher conductivity is higher than the antenna coated with chromium and nickel. In this paper, antennas were coated using different coating metal with reported work. The performance of the antennas observed by returns loss. The copper coated horn antenna is found to have the best performance in the five antennas due to low relative permeability and high conductivity.

Table 4. Comparison of proposed design with reported work.

Ref	Types of coating metal	Conductivity (S/m)	Frequency (GHz)	Gain (dB)	Return loss (dB)
[6]	Copper	5.800x107	12	17.3	-
[6]	Chromium	0.800x107	12	17.1	-
[6]	Nickel	1.440x107	12	16.9	-
This paper	Copper	5.980x107	5	15.06	18.5545
This paper	Aluminium	3.500x107	5	15.08	18.5548
This paper	Zinc	1.682x107	5	15.08	18.5559
This paper	Tin	8.700x107	5	15.08	18.5553
This paper	Mercury	1.044x107	5	15.07	18.5602

5. Conclusion

In CST Computer simulation, 15 dB horn antenna operating in the 5 GHz band was developed using a 3D FDM printer. The measured return loss has been obtained. The return loss of the antenna is applicable at almost 3.5 GHz since it is less than -10 dB. The lower return loss assures that the antenna is considered stable and suitable to be used in heart and respiration rate monitoring system. In terms of weight reduction and low cost, copper-coated 3D printed horn antenna was developed as an alternative to the current methods. The antenna simulation and measurement results were obtained in a frequency band of 3-11 GHz which covered the ultra-wide frequency range. This is means that the work done of applying UWB printed antenna for heart and respiration rate monitoring system. It is observed that because of low relative permeability and high conductivity, the copper-coated horn antenna has the great performance antenna. For future work it is also expected to develop other types of UWB antenna with commercial metallic style structures.

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