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Research Article

Application of Polyurethane Paint with Increased Electrical Conductivity and Flexibility on 3D Printed Waveguides

Abdullah Gozum*,[1], Taner Tekin[2], Oguzhan Akgol[3]

[1]Ataturk University, Chemical Engineering Department

[2]United Arab Emirates University, Electrical and Communication Engineering Department

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Abstract

WR-90 (X-band) and WR-62 (Ku-band) are among the most common waveguide sets used in several engineering areas particularly at high frequencies. Conventionally manufactured metallic waveguides are expensive to fabricate due to their need for highly sensitive machining processes. This study presents the development and application of conductive polyurethane-based coating on 3D-printed waveguide structures intended for high-frequency electromagnetic applications. This study presents the development and application of a conductive polyurethane-based coating on 3D-printed rectangular waveguides designed for X-band (8–12 GHz) and Ku-band (12.4–18 GHz) frequencies. Electromagnetic characterization of PLA was conducted to determine its relative permittivity and permeability, enabling accurate simulation of waveguide performance. The designed structures were evaluated using CST Microwave Studio to simulate signal transmission behavior, and the results were compared with Perfect Electric Conductor (PEC) models. The obtained results indicated that the coated waveguides exhibit transmission characteristics highly comparable to metallic ones, with over 99% transmission of electromagnetic waves at the frequencies higher than the cut-off frequencies in both X and Ku bands. The suggested approach offers a low-cost, lightweight, and customizable alternative for microwave and millimeter-wave systems and wherever the waveguides are needed.

1. Introduction

Waveguides are structures that allow electromagnetic waves to be transmitted from one point to another in a guided manner with minimal loss. Waveguides, which are applied in many areas such as radar systems, satellite communications and microwave engineering, can be made in various types. They are designed to transfer electromagnetic energy effectively, mostly with minimum loss, and especially to be used in high frequency systems such as coaxial cables where transmission lines are inefficient. Waveguides can be made rectangular, circular and flexible. The inner dimensions of these structures, which are made in the form of hollow pipes, determine the cut-off frequency [1-2]. This frequency point is the minimum frequency allowing the given propagation mode to be exist. The electromagnetic wave is attenuated exponentially for the frequencies lower than this specific frequency point rather than transmitting the electromagnetic signals.

Waveguides can be fabricated in different forms, including rectangular, circular, and flexible geometries, depending on the required frequency band and application. The inner dimensions of the waveguide directly determine the cut-off frequency, which defines the minimum frequency at which a mode can propagate [3]. Among these, rectangular waveguides are most commonly used, especially in X-band (8–12 GHz) and Ku-band (12.4–18 GHz) applications, where precise performance and minimal loss are required.

Waveguides are manufactured to operate in specific frequency bands and are sized according to the wavelength corresponding to these bands. Waveguides are generally manufactured by machining metal blocks. It is possible to produce the desired waveguide shapes with very precise machining. However, there are some disadvantages to this type of approach. High cost is known as the biggest disadvantage of this approach. Since it needs to be manufactured with high precision, especially at high frequencies, high-cost production methods must be used [4]. Therefore, the relevant approach causes cost and material loss. In waveguide applications, metal/metal alloys with high conductivity values are widely used. Although known manufacturing techniques are applied in the production of these structures, they are costly structures to obtain due to complex and delicate processes [5]. In study, it is aimed to coat the surfaces of waveguides produced using 3-D printers with the paint to be developed and to compare them with standard products.

With the rise of additive manufacturing technologies, especially Fused Deposition Modeling (FDM) 3D printing, it has become feasible to produce complex and lightweight structures using low-cost, non-conductive polymers like PLA or ABS. However, these materials lack the electrical conductivity needed for efficient high-frequency propagation. Therefore, post-processing methods such as surface metallization or conductive coatings have become essential for making such components functional [6]. This study aims to use a specially developed conductive polyurethane-based paint to coat the internal surfaces of 3D-printed waveguides. This approach enables the realization of lightweight, cost-effective, and customizable antenna structures while maintaining acceptable electromagnetic performance compared to waveguides produced using conventional methods. The proposed paint is applied after printing, optimizing the structure to ensure full reflection from the metal body. Surface roughness is crucial at this stage. Therefore, during the surface coating process, the application was carried out to optimize the skin depth (typically <10 μm at X-band) and surface roughness of the surface to maintain electromagnetic performance at desired level [7]. The

*Corresponding Author: ttekin@atauni.edu.tr
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skin depth is one of the most important parameters in the proposed system since it determines the thickness of the coating application along with the conductive properties. This parameter refers to the depth of the conductive material where the amplitude of an electromagnetic wave reduces its initial value by 37% at the surface.

It is clear from the mentioned properties that there is an increasing demand for low-cost, lightweight, and adaptable high-frequency components, alternative fabrication methods for waveguides in electromagnetic research. Additive manufacturing, when combined with conductive surface coatings, offers a promising pathway to address the limitations of conventional metal-based structures. In this study, it is aimed to investigate the feasibility and electromagnetic performance of X-band and Ku-band rectangular waveguides fabricated via 3D printing and internally coated with a conductive polyurethane-based paint. The purpose is to evaluate whether such coated structures can match or approximate the transmission behavior of traditionally machined metallic waveguides. The proposed system provides several novelties compared to traditional metallic waveguides. One of the most important feature of this approach is that it provides flexibility and elasticity unlike brittle metallic waveguides. Another feature provided by the system is that they are lightweight, cost efficient and customizable depending on the application area and needs. It is also clear that the manufacturing process for these waveguide system is easier compared to conventional metallic structures.

2. Materials and Methods

2.1. Test specimens and properties

The development of the conductive polyurethane-based coating was carried out in several systematic stages aimed at optimizing both the electrical conductivity and mechanical flexibility of the final formulation. The primary functional requirement was defined as achieving a maximum sheet resistance of 0.3 Ω/sq, ensuring suitability for high-frequency electromagnetic applications. By considering the sheet resistance and the skin depth, the thickness was optimized to be 30 microns for all applications included in the study.

Initially, raw material screening was conducted to identify and select conductive and elastomeric additives compatible with the polyurethane matrix. This included:

- Ensuring chemical compatibility between selected resins and conductive fillers,
- Testing a range of conductive additives (e.g., metal powders, carbon-based materials),
- Achieving the desired level of elasticity to maintain mechanical integrity on curved or flexible substrates,

In addition, the NCO: OH ratio was calculated and adjusted according to the targeted application method to achieve optimal curing kinetics and coating consistency. The final formulation was fine-tuned by optimizing drying and curing times to ensure uniform film formation, good adhesion, and the desired electromagnetic performance.

The conductive paint used in the presented study is formulated on a polyurethane-based binder system. Polyurethane, used as the binder, allows the coating to resist cracking on various surfaces such as metal, composite and polymer surfaces by providing high elasticity and multi-surface compatibility. Aluminum and copper-based metallic pigments were used as the phases for providing conductivity and nonionic agents were used to ensure a homogeneous distribution of these pigments. Furthermore, rheology agents compatible with polyurethane (modified polyurea, bentonite derivatives) were added to control application rheology of the coating. In this way sedimentation, flow on the surface and uneven thickness formation were prevented. The components used for the development of the conductive paint are tabulated along with their ratio and functions in the following table (Table 1).

Table 1. Components of the conductive paint, their functions and ratios

Component	Function	Contribution	Ratio (%)
Polyurethane Resin	Binder, flexibility and adhesion	Elasticity, resistance to cracking, multi surface compatibility	30-40
Metallic Pigments	Electrical conductivity	Absorption and reflection of electromagnetic waves	40-55
Agents	Homogeneous distribution of pigments	Continuous conductive structure, performance stability	0.5-2
Rheology Modifiers	Flow and application rheology control	Prevent precipitation and flow, provide uniform film formation	1-3
Additives	Film integrity and environmental resistance	Long lasting and stable coating	2-5

In order to ensure accurate simulation and performance analysis of the 3D-printed waveguides, we need to determine the electromagnetic behavior of the substrate material used (Polylactic Acid (PLA)). Specifically, the electrical permittivity (ε)and magnetic permeability (μ) of PLA were required to define the dielectric behavior of the waveguide structure in simulation environments. These parameters directly influence the propagation characteristics of the waveguide, including the cut-off frequency, impedance, and field distribution for supported modes, especially in the X-band and Ku-band ranges. These parameters are complex and consist of real and imaginary components as shown in the following equations.

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$$

$$\mu_r = \mu_r' - j\mu_r''$$

The real component corresponds to the stored energy, while the imaginary component represents the losses. These parameters express the energy storage capabilities and electromagnetic losses of a material to be measured under the influence of electric and magnetic fields (Figure 1).

Figure 1. Electrical permittivity and magnetic permeability of materials

Various standard techniques are used to obtain the complex electric permittivity (ε) and magnetic permeability (μ) of materials at different frequency ranges [8-9]. We have used waveguide electromagnetic characterization method to determine the electromagnetic characteristics of PLA used in 3D printing process. The sample size is suitable for fitting a sample holder of a Ku-band waveguide measurement set (Figure 2).

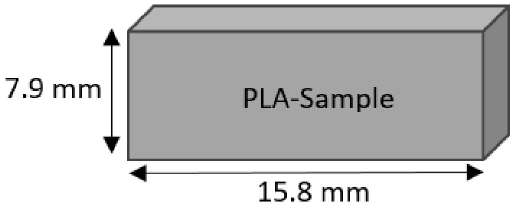

Figure 2. PLA sample size for waveguide measurement setup (Thickness of 4 mm)

The waveguide measurement setup is composed of a Vector Network Analyzer, two waveguides including adaptors and a sample holder as shown in the following figure (Figure 3).

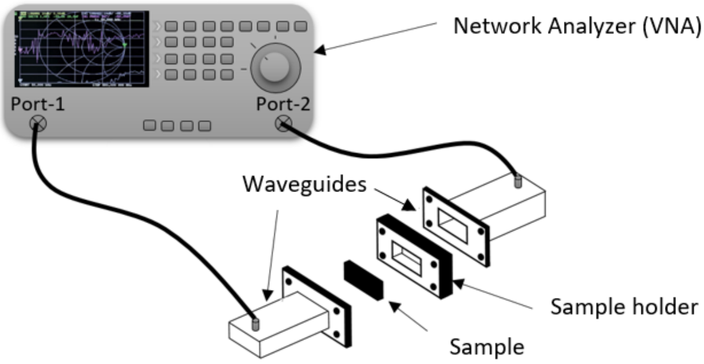

Figure 3. Waveguide measurement setup

After obtaining the electrical permittivity and magnetic permeability values of the PLA samples used as substrates, the electromagnetic behavior of the developed paint was investigated using rectangular waveguides and the simulations were performed for waveguides operating in two different frequency bands. The simulations were performed using CST Microwave Studio, a commercial electromagnetic simulation software. A basic rectangular waveguide is shown in the figure below. No adapters were used during the simulation, and waveguide ports were assigned to both openings of the waveguides (Figure 4).

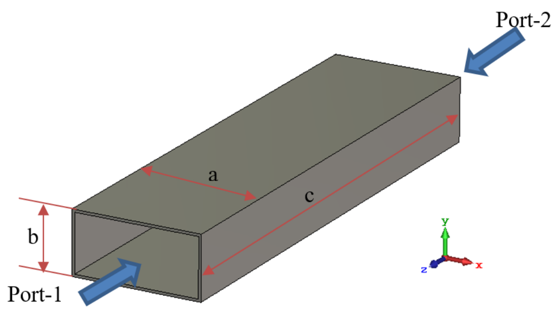

Figure 4. Rectangular Waveguide

Table 2. Frequencies and dimensions of the waveguide sets considered in the study

Waveguide band	Frequency Range (GHz)	Cut-off Freq. (GHz)	Width-a (mm)	Height-b (mm)
X-Band	8-12	~6.56	22.86	10.16
Ku-Band	12.4-18	~9.49	15.80	7.90

The detailed dimensions of the corresponding waveguides are given in Table 2. It should be noted that the lengths for both sets are equal and c=100 mm. For such waveguides, the cutoff frequency for the TE_{mn} mode can be calculated as:

$$f_{c_{mn}} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$$

Here, f_c is the cutoff frequency (Hz), μ corresponds to the magnetic permeability of the material, ε is the electrical permittivity, m and n are the modes of the waveguide, a and b are the geometric dimensions of the waveguide (horizontal and vertical, respectively). We will be interested in the fundamental mode, which will be TE_{10}. For this mode, m=1 and n=0, and the formula can be simplified as follows:

$$f_{c_{10}} = \frac{c}{2a}$$

One can see that c is the speed of light, which is $3x10^8$ m/s. As a general approach, in rectangular waveguides, the height is usually chosen as half the width (b=a/2) [1].

2.2. Results and Discussion

The study focused only on two common waveguide sets, X band and Ku band. The first structure, coded as a WR-90 rectangular waveguide, is a standard structure operating in the X-band (8-12 GHz). During the simulation, the waveguide dimensions were set to a = 22.86 mm and b = 10.16 mm, and its length was set to c = 100 mm. The calculated cutoff frequency is 6.557 GHz for the TE_{10} mode. A screenshot and detailed dimensions of the designed structure are shown below. During the simulation, both the recommended paint coating and a perfect conductor (PEC) were used. It should be noted that the coating was applied only to the inner surface. This is sufficient for the inner section where EM reflection is required. PLA, commonly used in 3-D printers, was used as the coated surface. Electromagnetic characterization was made for PLA and the results are given in the following figure (Figure 5). As seen in the figure, the real part of the electrical permittivity of PLA stays almost constant at 18 while the imaginary part is very close to zero level. Since the substrate (PLA) has no magnetic property, magnetic permeability values are found to be 1+j0. Therefore, permeability graph is not shown in the study.

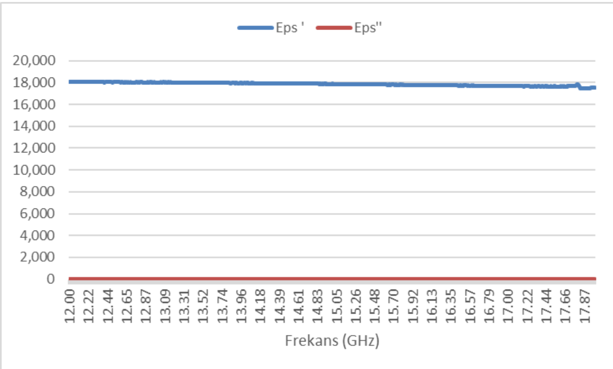

Figure 5 Electrical permittivity values for PLA

Two ports are assigned as waveguide ports in the program and the transmission behavior was obtained to make the comparison between the proposed paint and the PEC waveguide model (Figure 5).

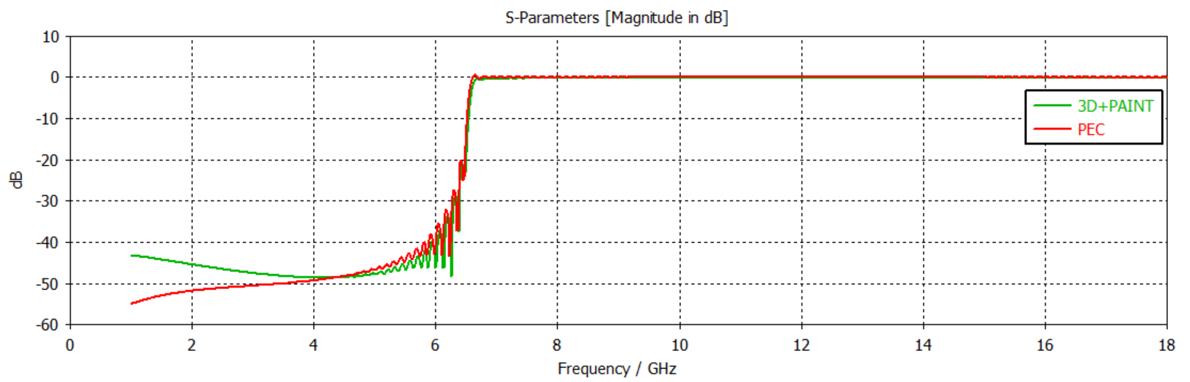

Figure 5. Comparison between 3D printed substrate with conductive paint and PEC for X-band waveguide (Transmission $S_{12}=S_{21}$)

As seen in the figure on transmission behavior of the waveguide, there is almost no transmission up to cutoff frequency. It is less than -40 dB level which means that almost all of the incident electromagnetic energy reflected from the waveguide to the source port. After the cutoff frequency, the level is almost 0 dB up to 18 GHz meaning that all of the energy is transmitted. This behavior is the expected one for a waveguide. It is clear that both PEC and 3D+Paint versions act almost the same meaning that our proposed approach can easily be used instead of PEC.

As another application, Ku band waveguide was prepared and tested. The rectangular waveguide, also known as WR-62, is a standard structure used for Ku-band applications that operate effectively in the frequency range from 12.4 to 18 GHz. In this study, the waveguide dimensions were selected as a = 15.8 mm, b = 7.9 mm, and length c = 100 mm, resulting in a cutoff frequency of approximately 9.5 GHz for the TE_{10} mode. Electromagnetic simulations were also performed across a wide frequency band from 1 to 18 GHz to evaluate the transmission characteristics and compare the performance of the two configurations. The same scenario was repeated using a 3D-printed structure, one with a metal (PEC) surface and the other coated with a conductive polyurethane-based paint. This comparison allows us to evaluate the practicality of using functional coatings, particularly in Ku-band systems where weight reduction, conformal integration, or cost-effectiveness are critical. The following figure shows the transmission behavior of the waveguide operating at Ku band.

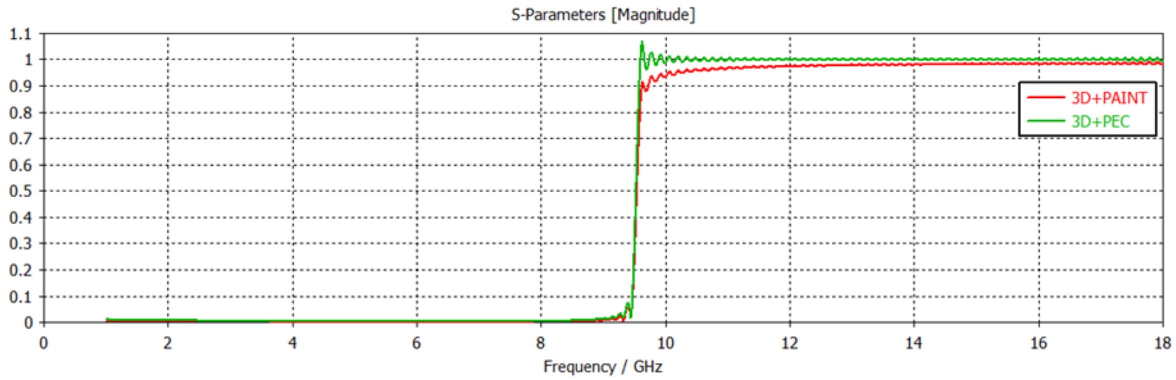

Figure 6. Comparison between 3D printed substrate with conductive paint and PEC for Ku-band waveguide (Transmission S_{12}=S_{21})

Similar behavior to the X-band waveguide was observed in the Ku-band simulation. To show how much energy is transferred in percentage, the graph is given in linear form instead of giving in decibels. After the cutoff frequency, almost 99% of the energy is transferred and very close to PEC waveguide.

Furthermore, it can be seen from the obtained results that the increased elasticity of the polyurethane-based system did not only enhanced the electromagnetic performance of the coating but it also widened the application variety of the suggested system to various surfaces. It should also be noted that the conventional conductive paints often have limited application due to their hardness and brittleness levels preventing to be applied on elastic surfaces having the possibility of facing different environmental conditions.

Nomenclature

PEC	: Perfect Electric Conductor
PLA	: Polylactic Acid
f_c	: The Cutoff Frequency
a	: Width of the Waveguide
b	: Height of the Waveguide

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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