Performance Analysis of 3D-Printed X-Band Horn Antenna Coated with Different Conductive Materials

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Abstract: This study evaluates the performance of 3D-printed X-band horn antennas, focusing on designs fabricated with additive manufacturing (AM) methods and coated with various conductive materials. Conductive coatings like silver paint, copper tape, and copper plating were applied to examine their effects on antenna performance. Key metrics assessed include gain, reflection coefficient, and voltage standing wave ratio (VSWR). Findings indicate that the copper-plated antenna demonstrates superior performance, with the highest gain and lowest reflection coefficient among all tested materials.

1 INTRODUCTION

Antennas are critical in communication systems, especially in satellite and wireless communication. X-band antennas are preferred for high-frequency applications like radar, telecommunications, and weather monitoring due to their directivity, low power loss, and high gain(A. I. Dimitriadis, 2017). Traditional metallic fabrication methods result in heavy, costly designs. This research explores AM techniques as lightweight, cost-effective alternatives(M. Kilian, 2017). Conductive coatings—silver paint, copper tape, and copper plating—are applied to determine which offers the best antenna performance(S. Verploegh, 2017).

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1.1 Motivation

Exploring AM enables lightweight, customizable antenna designs that are not feasible with conventional manufacturing. Testing different conductive coatings may lead to an accessible, high-frequency antenna solution, reducing the need for metals and costly machining. Potential applications extend to aerospace, telecommunications and defense industries.

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1.2 Problem Statement

Traditional metal-based antennas are heavy and costly, with limited scalability. This study investigates whether 3D-printed antennas with conductive coatings can retain high gain, low reflection coefficient, and effective impedance matching, providing a viable, lightweight alternative.

Table 1: Developing Antenna Specifications.

1	Frequency	(8-12) GHz
2	Height	1.016 cm
3	Width	2.286 cm
4	Return loss	(-25 to -50) dB
5	Antenna Gain	(10-25) dB
6	VSWR	1

Based on the requirement a WR-90 Rectangular waveguide is selected as the operating frequency range is in the frequency range of X band 8 to 12 GHz.

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2 LITERATURE REVIEW

Horn antennas have been developed since the 20th century for radar and satellite applications, with Roy et al. documenting their evolution(H. Yao, 2017). Yao et al. demonstrated the use of copper-based coatings on 3D-printed antennas, achieving competitive gain and reflection coefficients in Ka-band applications. Chuma et al. found that copper-plated 3D-printed antennas perform well at X-band frequencies, with superior impedance matching over alternatives like silver paint or copper tape.

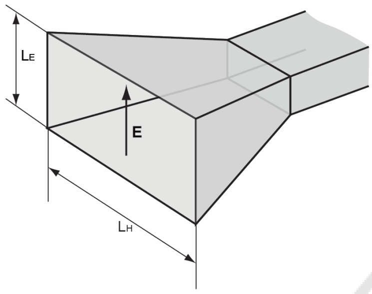

Figure 1: Pyramidal Horn Antenna

Figure 2: Different types of coatings used

3 METHODOLOGY

3.1 Design and Fabrication

Three identical horn antennas were designed with CAD and fabricated using Fused Deposition Modeling (FDM) with ABS plastic. Each was coated with silver paint, copper tape, or copper plating(S. Verploegh, 2017). A carbon layer was added before electroplating for improved adhesion on the copper-plated antenna.

3.2 Designing of Pyramidal Horn Antenna

The design of a pyramidal horn antenna involves precise calculations to ensure efficient signal propagation and minimal reflection losses. The following parameters are critical to the design process:

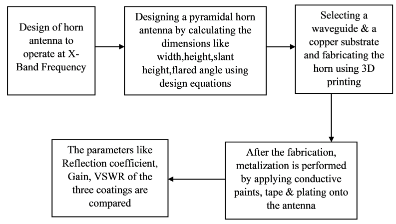

Figure 3: System Design

3.2.1 Flared Dimensions

The flared angle of the horn antenna is calculated using:

$$\Psi_e = \tan^{-1}\left(\frac{B_1}{2L_E}\right) \tag{1}$$

where:

$$B_1 = \sqrt{2\lambda L_E}$$

and L_E is the slant height in the E-plane.

3.2.2 Aperture Dimensions

The aperture dimensions for the E-plane and H-plane are given by:

$$a = \frac{\lambda_0}{2} \quad \text{and} \quad b = \frac{\lambda_0}{4} \tag{2}$$

where λ_0 is the free-space wavelength.

3.2.3 Directivity

The directivity of the horn antenna is calculated as:

$$D = \frac{4\pi A}{\lambda^2} \tag{3}$$

where A is the aperture area and λ is the operating wavelength.

3.3 Simulation and Testing

HFSS software simulated gain, VSWR, and reflection coefficient for each coating. The test was performed with a Vector Network Analyzer (VNA), which measures return loss, impedance matching, and radiation patterns. Simulated and measured results were compared for accuracy.

3.4 Mapping of the Design into Software

The designed pyramidal horn antenna was implemented using HFSS (High-Frequency Structure Simulator). The mapping process involved the following steps:

3.4.1 3D Model Creation

The CAD model of the antenna was created based on the calculated parameters. The software allowed for precise modeling of flare angles, aperture dimensions, and waveguide sections.

3.4.2 Material Assignment

Material properties such as conductivity and permittivity were assigned to the model. For example:

$$\sigma_{\text{copper}} = 5.8 \times 10^{7}\,\text{S/m} \tag{4}$$

3.4.3 Boundary Conditions and Excitation

Boundary conditions were set to mimic real-world environments. Waveguide port excitation was applied at the input to simulate signal propagation.

3.4.4 Simulation Setup

The frequency range was set to 8 GHz to 12 GHz, and performance metrics such as gain, S11, and VSWR were analyzed.

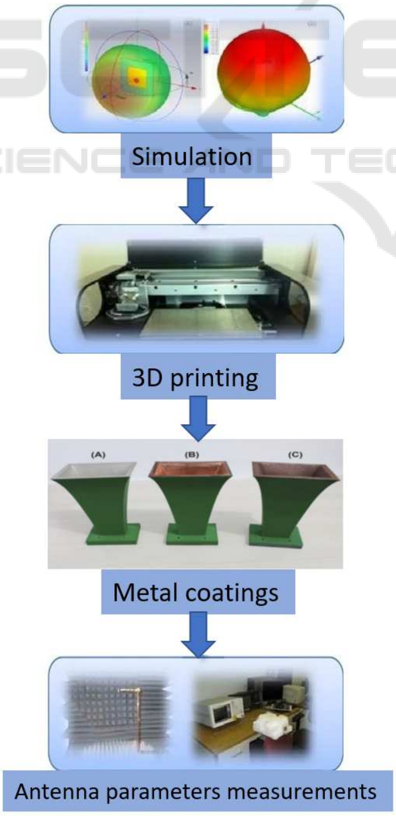

Figure 4: Antenna Fabrication Process

4 RESULTS AND DISCUSSION

4.1 Gain Comparison

The copper-plated antenna showed the highest gain, probably due to copper's high conductivity and minimized resistive losses(E. L. Chuma, 2019). Silver and copper tape coatings showed lower gain, which could be attributed to challenges in uniformity and conductivity(D. Nagaraju, 2021a).

The gain of the horn antenna was observed to be highest for copper-plated designs:

$$G = 20\,\text{dB} \quad \text{at}\,10\,\text{GHz} \tag{5}$$

4.2 Reflection Coefficient (S11)

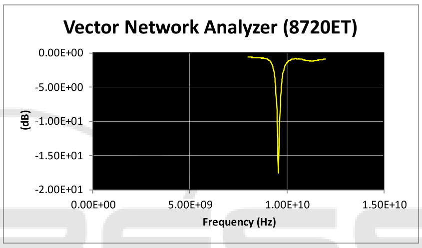

Figure 5: Reflection coefficient of silver painted horn Antenna

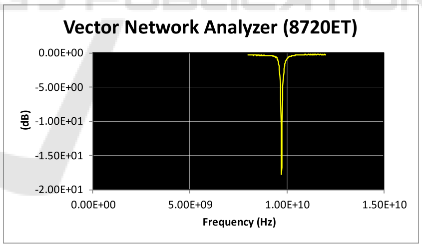

Figure 6: Reflection coefficient of Copper taped horn Antenna

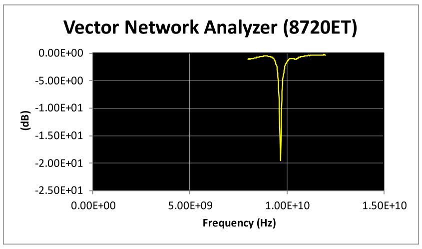

Figure 7: Reflection coefficient of Copper plated horn Antenna

Copper-plated antennas had the lowest reflection coefficient (S11) values, with less signal loss compared to silver paint and copper tape, whose S11 values were higher due to surface roughness(D. Nagaraju, 2021b).

The reflection coefficient values for the different coatings are

$$S11_{\text{copper}} = -15\,\text{dB} \tag{6}$$

$$S11_{\text{silver}} = -10\,\text{dB} \tag{7}$$

4.3 VSWR

VSWR results for the copper-plated antenna indicated near-ideal impedance matching with VSWR close to 1. Silver and copper tape coatings had slightly higher VSWR values, reducing transmission efficiency.

The results obtained from simulations and practical measurements are summarized below.

The VSWR values indicate efficient impedance matching for copper plating:

$$\text{VSWR}_{\text{copper}} = 1.2 \tag{8}$$

$$\text{VSWR}_{\text{silver}} = 1.5 \tag{9}$$

4.4 Radiation Patterns

The radiation patterns were consistent with theoretical predictions, showing high directivity in the main lobe for all designs.

5 CONCLUSION

This study demonstrates the effectiveness of copper plating for 3D-printed X-band antennas, supporting the feasibility of AM as a lightweight, cost-efficient alternative. Future studies can explore new conductive materials, printing techniques, and hybrid materials to optimize antenna performance.

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