Impact of Copper (Cu) and Lead (Pb) Conductive Materials on the Radiation Performance of Printed Circuit Dipole Antennas

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Abstract

This study examines how copper (Cu) and lead (Pb) conductors influence the radiation performance of a printed-circuit dipole antenna. Numerical analysis was carried out using the Finite-Difference Time-Domain (FDTD) method to evaluate key parameters such as resonant frequency, wavelength, characteristic impedance, VSWR, return loss, and radiated power. The copper-based antenna resonates at 2.465 GHz with a radiated power of 0.366 W, while the lead-based design resonates at 2.460 GHz and radiates 0.365 W. Both antennas achieve strong impedance matching, as reflected by similar VSWR values of approximately 1.08. Although the lead-based antenna shows slightly lower return loss (−28.093 dB) and reflection coefficient (0.0394), copper provides marginally higher transmission efficiency due to its superior electrical conductivity, which reduces resistive losses. Overall, the performance gap between the two materials is minimal; however, copper offers a slight advantage, particularly for applications requiring high radiation efficiency and stable operation at 2.4 GHz. These findings underscore the importance of selecting appropriate conductor materials to optimize antenna performance in wireless communication systems.

Keywords: *Antenna, Cu, Dipole, Pb, Printed Circuit.*

I. INTRODUCTION

ANTENNAS are a vital part of modern communication systems because they act as a bridge between electrical signals and electromagnetic waves [1]. Their performance directly affects how well wireless devices can send and receive information. When an antenna works, it takes electrical signals from a transmission line and turns them into electromagnetic waves that travel through space [2]. It can also capture electromagnetic waves from its surroundings and convert them back into electrical signals [3][4]. To judge how well an antenna performs, engineers usually look at several factors such as operating frequency, bandwidth, return loss, impedance, reflection coefficient, and radiation efficiency [5].

Among the many antenna types used today, the printed-circuit dipole antenna is one of the most popular. Unlike a traditional dipole made from metal rods or wires, this version is printed on a dielectric board using PCB manufacturing techniques [6]. This design offers clear advantages: it is compact, lightweight, inexpensive to produce, and easy to integrate with modern electronics like Wi-Fi modules, IoT devices, and wireless sensors. Because of these benefits, printed-circuit antennas are widely used in space-constrained wireless applications [7].

Several elements influence how well a printed-circuit dipole antenna performs, including the antenna's shape, the characteristics of the substrate material, and the type of conductor used [8]. The conductive material is especially important because it determines electrical conductivity and affects how much power is lost before radiation occurs. Materials with higher conductivity help reduce loss and improve radiated power [9]. Copper (Cu) is commonly chosen for this reason, as it has excellent conductivity, low electrical loss, and tends to produce strong radiation performance [10]. However, lead (Pb) has lower conductivity and a much higher density, which can introduce more resistive loss and reduce radiation output [11].

To analyze how conductor choice influences antenna behavior, this research uses the Finite-Difference Time-Domain (FDTD) method. FDTD is a numerical technique that models electromagnetic wave behavior over time and space, allowing researchers to simulate antenna performance without physically building prototypes [12][13]. With this method, characteristics such as resonant frequency, return loss, VSWR, impedance, and radiated power can be observed accurately and efficiently [14]. Using simulation also makes it easier to compare material-based differences in electromagnetic performance before moving to real-world fabrication [15].

The main goal of this study is to compare the radiation behavior of printed-circuit dipole antennas made with Cu and Pb. Through this comparison, the research aims to help define which material is more suitable for efficient antenna design in wireless communication applications. The results are expected to support ongoing development in printed-circuit antenna technology and help guide material selection for future compact and energy-efficient wireless systems.

II. MATERIALS AND METHODS

A. *Materials and Parameters*

In this study, a rectangular printed-circuit dipole antenna is used as the primary model. The antenna is designed to operate in the 2.4 – 2.5 GHz range, which falls within the Industrial, Scientific, and Medical (ISM) band and is widely utilized in modern wireless communication applications [16].

The substrate employed for the antenna structure is FR-4 epoxy, featuring a thickness of 1.61 mm, a relative permittivity (ε_r) of 4.43, and a loss tangent of 0.02. To evaluate material influence on antenna performance, two conductor options are compared: Cu with an electrical conductivity of 5.8×10^7 S/m and Pb with a conductivity of 4.55×10^6 S/m.

The dipole elements are designed with a length of 18 mm and a width of 4 mm. Owing to the symmetry of the dipole configuration, no ground plane is incorporated. The antenna is excited through a waveguide port setup, ensuring proper signal feeding and simulation accuracy.

B. *Antenna Geometry Design*

The first step of this work is the design of the printed-circuit dipole antenna using the Finite-Difference Time-Domain (FDTD) method. Two antenna models are prepared Cu and Pb, while keeping all geometric dimensions and structural parameters identical. A dipole configuration is chosen because it offers a simple structure, good radiation performance, and is commonly used as a benchmark in electromagnetic studies. Key physical parameters, including element length, spacing, and conductor thickness, are selected to ensure that the antenna resonates within the 2.4 GHz ISM band.

C. *Simulation Procedure*

The electromagnetic performance of each antenna model is evaluated through FDTD-based simulation. A waveguide port is used to excite the antenna, and the resulting electromagnetic field response is analyzed. Several performance indicators are observed, including return loss, reflected power, bandwidth, voltage standing-wave ratio (VSWR), mismatch loss, forward power, and total radiated power. The simulation runs until numerical stability is achieved to ensure reliable and representative results.

D. *Simulation Procedure*

The simulation output from both conductor models is compared primarily through the S-parameter (S11) curve to identify resonance frequency and radiation efficiency. Additional analysis focuses on evaluating how each conductor material influences energy radiation and power efficiency. By examining these performance differences, the study aims to determine which material Cu or Pb provides better suitability for printed-circuit dipole antenna applications, especially where high radiation efficiency is required.

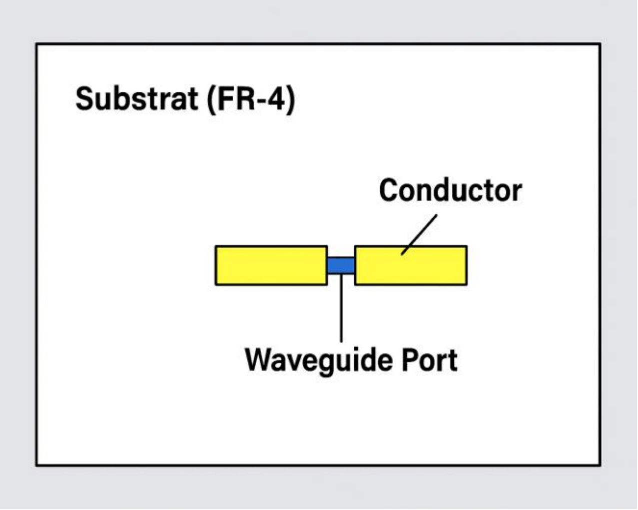


Figure 1. Printed-circuit dipole antenna

III. RESULTS AND DISCUSSIONS

The printed-circuit dipole antenna was simulated using two types of conductor materials, namely copper and lead. The numerical computation was performed using the Finite-Difference Time-Domain (FDTD) method. The comparison of simulation results is presented in Table 1.

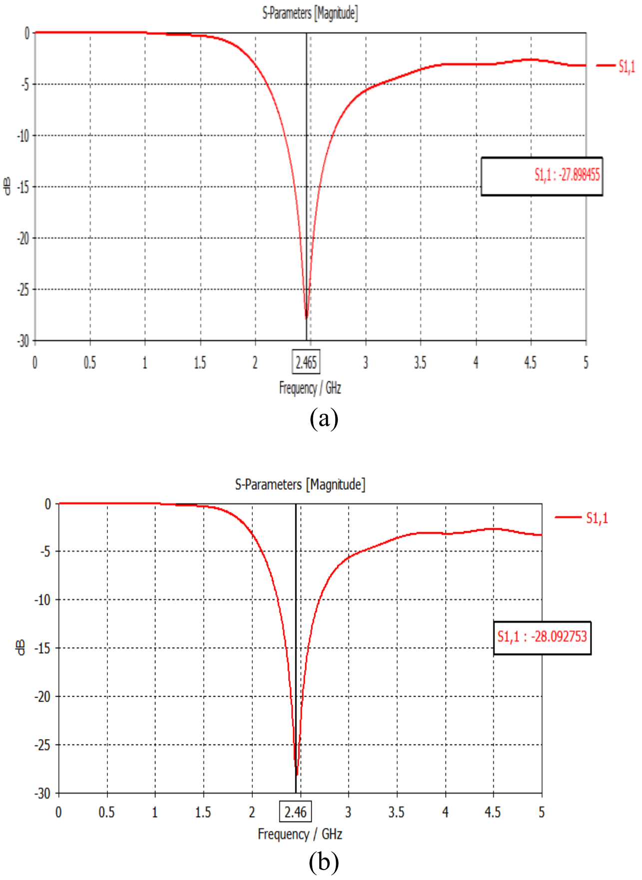
Table 1. Comparison of Printed-Circuit Dipole Antenna Performance Using Copper (Cu) and Lead (Pb) Conductors

Antenna Parameter	Copper (Cu)	Lead (Pb)
Resonant Frequency (GHz)	2.465	2.460
Wavelength (mm)	67.35	67.49
Characteristic Impedance (Ω)	46.663	46.466
Phase (°)	147.79	157.62
VSWR	1.083	1.082
Bandwidth (GHz)	0.451	0.450
Reflection Coefficient	0.0398	0.0394
Return Loss (dB)	−27.898	−28.093
Reflected Power (%)	0.158	0.155
Mismatch Loss (dB)	−68.849	−67.470
Forward Power (%)	99.842	99.844
Radiated Power (W)	0.366	0.365

The antenna constructed from Cu shows a slightly higher resonant frequency than the one made from Pb. This difference can be attributed to the superior electrical conductivity of Cu, which reduces conduction losses and supports a faster resonant response. As a result, electromagnetic waves propagate more efficiently along the Cu surface, producing a marginally shorter wavelength.

Both antenna designs achieve characteristic impedances close to the ideal 50 Ω standard, with values of 46.663 Ω for Cu and 46.466 Ω for Pb. The corresponding VSWR values, approximately 1.08 for both. These is indicate strong impedance matching with the transmission line.

Interestingly, the Pb-based antenna exhibits a slightly lower reflection coefficient, suggesting a small reduction in reflected power. This trend is consistent with the return loss values, where Pb achieves −28.093 dB compared to −27.898 dB for Cu. These results confirm that both materials provide effective impedance matching. Figure 2 presents the resonant frequency and return loss behavior for each conductor.



(a)
(b)

Figure 2. Return Loss Response of Printed-Circuit Dipole Antenna: (a) Cu Conductor, (b) Pb Conductor

Both materials demonstrate exceptionally low reflected power (approximately 0.15%). Copper provides slightly lower mismatch loss (−68.849 dB) compared to lead (−67.470 dB), indicating that nearly all input energy is efficiently transferred to the antenna with only negligible loss.

One of the key performance indicators in this study is radiated power. The copper conductor produces a radiated power of 0.366 W, which is marginally higher than the 0.365 W produced by the lead-based design. Although the difference is relatively small (around 0.27%), the results reinforce the principle that materials with higher electrical conductivity support better radiation efficiency, as reduced internal resistance minimizes energy dissipation within the structure.

Beyond electrical conductivity, the intrinsic physical properties of each material also contribute to overall antenna performance. Cu has a density of 8.96 g/cm^3, lower than Pb (11.34 g/cm^3), but exhibits conductivity nearly six times greater. At microwave frequencies (e.g., 2.4 GHz), the skin effect becomes dominant, confining current to the conductor surface. Materials with high conductivity produce smaller surface resistance, thereby reducing conduction losses [17]. Consequently, although Pb can reflect electromagnetic energy, greater absorption losses occur within the material, reducing radiation efficiency compared to Cu.

In printed-circuit configurations, conductor loss tends to dominate over dielectric loss when using low-loss substrates [18]. In this context, Cu provides superior overall efficiency. From a manufacturing and environmental standpoint, Pb is also disadvantageous due to its toxicity, environmental hazards, and comparatively lower mechanical stability. Thus, Cu remains more suitable for long-term and commercial antenna applications.

IV. CONCLUSIONS

The performance differences between Cu and Pb conductors in printed-circuit dipole antennas are relatively small but consistent. Cu demonstrates slightly higher radiation efficiency due to its superior electrical conductivity, which minimizes power dissipation along the conductor surface. Although Pb shows marginally better reflection-related parameters (such as return loss and reflected power), Cu provides better overall radiation performance.

Therefore, for applications where radiation efficiency, electrical performance, and material reliability are critical, Cu remains the preferred conductor material for printed-circuit antenna design.

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