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Comparison of Silver and Aluminum Patches on the Electromagnetic Radiation of a Microstrip Dipole Antenna

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ABSTRACT

This paper compares silver (Ag) and aluminum (Al) as patch materials for a microstrip dipole antenna to examine how their electrical conductivities affect electromagnetic radiation performance. Both antennas were designed with identical geometrical and substrate parameters using the Finite-Difference Time-Domain (FDTD) method, varying only the patch material. Simulation results show that the resonant frequencies are 2.4700 GHz for Ag and 2.4649 GHz for Al. Both materials exhibit reflected power below 0.2% and have nearly identical radiated power, namely 0.3647 W for silver (Ag) and 0.3646 W for aluminum (Al). Overall, silver and aluminum demonstrate almost identical radiation characteristics. Silver offers slightly better conductivity, while aluminum provides similar efficiency at lower cost, making it a practical alternative for lightweight and economical microstrip antenna applications.

1. INTRODUCTION

Microstrip antennas have become one of the most widely used antenna types in modern wireless communication systems due to their low profile, light weight, and ease of fabrication (Siregar et al., 2022). These antennas are commonly employed in applications such as satellite communication, radar systems, mobile devices, and wireless sensor networks (Rahmat-Samii & Densmore, 2014). The performance of a microstrip antenna is strongly influenced by several parameters, including substrate properties, patch geometry, feeding technique, and the electrical characteristics of the conductive material used for the patch (Mishra et. al., 2022).

Among these factors, the choice of patch material plays a crucial role in determining the antenna's radiation efficiency, gain, and other electromagnetic performance (Siregar et al., 2023). The electrical conductivity, surface smoothness, and corrosion resistance of the material directly affect the current distribution and power loss within the antenna structure (Banerjee et al., 2025). Copper is commonly used as a standard conductive material due to its high conductivity and reasonable cost (Al-Gburi et. al., 2024). However, alternative materials such as silver (Ag) and aluminum (Al) are often considered for specific design requirements (Helena et al., 2020).

Silver is known for having the highest electrical conductivity among all metals, which can lead to improved radiation efficiency and reduced conductor losses (Bouafia et al., 2021). Aluminium, on the other hand, offers a lighter weight and lower cost, making it suitable for applications that require mass reduction or economic efficiency (Chen, 2023). Despite its lower conductivity compared to silver, aluminum remains a practical alternative in many engineering applications (Czerwinski, 2024). Silver (Ag) and aluminum (Al) are metallic elements that exhibit distinct crystallographic and electronic structures, which significantly influence their electrical and electromagnetic properties (Taher et al., 2018).

Silver (Ag) possesses a face-centered cubic (FCC) crystal structure with a lattice constant of approximately 4.09 Å. In this arrangement, each silver atom is surrounded by twelve nearest neighbors, forming a densely packed lattice that contributes to its high electrical and thermal conductivity. The atomic configuration of silver is [Kr] $4d^{10}$ $5s^1$, indicating one loosely bound valence electron in the 5s orbital. This delocalized electron allows efficient conduction of electric current and supports strong surface plasmon resonance, making silver an excellent material for high-frequency and low-loss antenna applications (Cheng et al., 2015).

Aluminum (Al) also crystallizes in a face-centered cubic (FCC) structure, with a slightly smaller lattice constant of 4.05 Å. Its electronic configuration, [Ne] $3s^2$ $3p^1$, provides three valence electrons that participate in metallic bonding. Although aluminum has lower electrical conductivity than silver due to stronger electron scattering and lower carrier density, it offers advantages in terms of low density, corrosion resistance, and mechanical strength (Nakashima, 2020). The similar FCC structures of both metals result in comparable electromagnetic behavior, while differences in electron density and conductivity explain the minor variations observed in antenna performance when substituting silver with aluminum (Abdelrahman et al., 2021).

This study presents a comparative analysis of silver and aluminum as patch materials for a microstrip antenna using FDTD method simulation. The main objective is to evaluate how differences in material conductivity and physical properties influence the antenna's electromagnetic radiation characteristics, including return loss, radiation efficiency, and gain. The results of this investigation are expected to provide insights for optimizing material selection in microstrip antenna design, balancing between performance and cost-effectiveness.

2. METHOD

2.1. Antenna Design Overview

The microstrip antenna in this study is based on a dipole configuration designed to operate within the Industrial, Scientific, and Medical (ISM) frequency band 2.4 – 2.4835 GHz. The antenna structure consists of a conductive patch, a dielectric substrate, and a ground plane (Siregar et al., May 2023). The design was analyzed and simulated using the Finite-Difference Time-Domain (FDTD) method, which offers a comprehensive full-wave electromagnetic evaluation (Teixeira et al., 2023).

The antenna's geometry was kept constant for both materials to ensure that any performance variation arises solely from the conductive properties of the patch materials (Siregar, 2018). The dimensions of the antenna were determined from standard microstrip design equations, with the resonant frequency, dielectric constant, and substrate thickness taken into account to achieve optimal impedance matching at the target frequency (Sharma, et al., 2017).

2.2. Patch Materials

Two conductive materials, silver (Ag) and aluminum (Al), were used for the antenna patch. The selection of these materials was based on their distinct electrical conductivities and physical characteristics, which influence current distribution and radiation performance. The electrical conductivity of silver is approximately 6.3×10^7 S/m, while aluminum has a conductivity of around 3.5×10^7 S/m (Rutledge, 1978). Both materials were assumed to have smooth and uniform surfaces in the simulation to minimize the effect of surface roughness.

The thickness (h) of each patch was set to 0.1 mm, providing an optimal balance between mechanical stability and minimal conductor loss. The length of the dipole arm was fixed at 50 mm, which corresponds to approximately half of the guided wavelength at the target resonant frequency within the selected substrate medium. The width of each patch was maintained at 18 mm to achieve proper impedance matching and to support efficient surface current distribution.

Table 1. Characterization of materials

Material	Electrical Conductivity (S/m)	Density (g/cm³)	Remarks
Silver (Ag)	6.3×10^7	10.5	Highest conductivity; high cost
Aluminum (Al)	3.5×10^7	2.7	Lightweight; lower conductivity

These dimensions were determined based on standard microstrip antenna design principles, taking into account the operating frequency, substrate permittivity, and effective wavelength in the dielectric medium. Maintaining of consistent geometry for both materials, the study isolates the effect of electrical conductivity on the antenna's electromagnetic radiation characteristics, such as return loss, VSWR, and radiation efficiency.

2.3. Substrate Specification

A FR-4 epoxy substrate was used for both antenna models, selected for its availability and widespread use in low-cost microwave circuits. The substrate parameters were set as follows:

- Relative permittivity (ε_r): 4.4
- Loss tangent ($tan\ \delta$): 0.02
- Thickness (h): 1.6 mm
- Length: 100 mm
- Width: 50 mm

The ground plane was modeled as a perfect electric conductor (PEC) to ensure consistent boundary conditions during simulation.

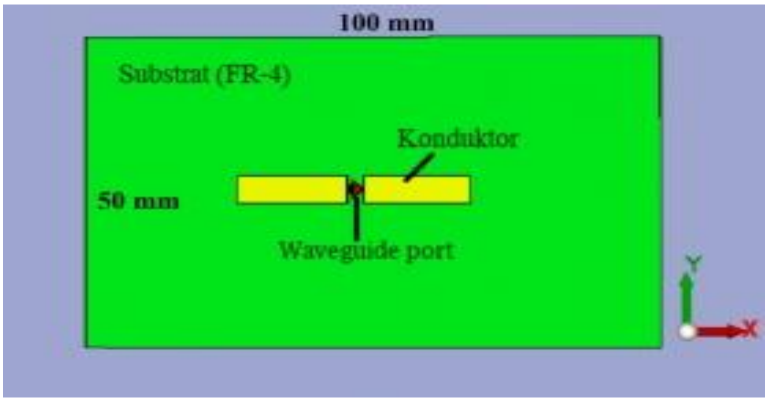

Figure 1. Design of Microstrip Dipole Antenna

2.4. Simulation Setup

The antenna models were simulated using FDTD method under identical boundary and excitation conditions. The FDTD simulation method is a numerical technique used to analyze electromagnetic wave propagation by directly solving Maxwell's equations in the time domain (Tamimah et al., 2023). The excitation was applied through a waveguide port positioned at the feed line to excite the dipole symmetrically. Open (add space) boundary conditions were applied to emulate free-space radiation.

The key electromagnetic parameters used to evaluate the performance of the microstrip dipole antenna include return loss (RL), reflection coefficient (Γ), reflected power, mismatch loss (ML), voltage standing wave ratio (VSWR), accepted power, forward power, and radiated power (Siregar et al., November 2022). The corresponding mathematical expressions are presented as follows:

- Return Loss (S_{11}) to determine impedance matching.
- VSWR expresses the degree of impedance matching between the antenna and the transmission line. Ideally, a perfectly matched antenna has VSWR = 1.
- The reflection coefficient describes the ratio of the reflected wave amplitude to the incident wave amplitude at the antenna input.
- Reflected power indicates the percentage of the input power that is reflected back due to impedance mismatch between the feed line and the antenna.
- Mismatch loss quantifies the power loss resulting from reflection at the antenna port. Lower mismatch loss implies better power transfer from the feed to the antenna.
- The accepted power is the portion of input power actually delivered to the antenna
- The forward power percentage defines the ratio of accepted power to input power
- Radiated power is the total electromagnetic power emitted by an antenna into free space. It represents the portion of the accepted input power 0.5 W that is converted into propagating electromagnetic waves rather than being lost as heat or reflected back toward the source.

Each simulation was performed across a frequency range of 2.0 – 3.0 GHz to identify the resonant frequency and bandwidth variations caused by the different patch materials (Rano et al., 2020).

3. RESULTS AND DISCUSSION

Table 2 presents a comparative analysis of the simulated performance parameters for microstrip dipole antennas using silver (Ag) and aluminum (Al) as the patch materials. The results indicate that both materials exhibit nearly identical electromagnetic characteristics, with only slight numerical variations in their respective performance metrics.

Table 2. Comparison of Silver (Ag) and Aluminum (Al) Materials

Parameters	Silver (Ag)	Aluminum (Al)
Frequency (GHz)	2.4700	2.4649
Wavelength (mm)	67.215	67.354
VSWR	1.0839	1.0836
Reflection Coefficient	0.0403	0.0401
Bandwidth (dB)	0.4584	0.4581
Phase	146.45^0	157.70^0
Characteristic impedance (Ω)	46.707	46.396
Return Loss (dB)	-27.897	-27.923
Reflected Power (%)	0.162	0.160
Mismatch Loss (dB)	-0.00706	-0.00698

Forward Power (%)	99.837	99.839
Radiated Power (W)	0.3647	0.3646

The resonant frequency for the silver patch is observed at 2.4700 GHz, while aluminum resonates at 2.4649 GHz. This minor frequency shift (approximately 0.0051 GHz) can be attributed to the slightly lower electrical conductivity of aluminum compared to silver, which affects surface current distribution and electromagnetic wave propagation. Consequently, the wavelength is marginally longer for aluminum 67.354 mm than for silver 67.215 mm.

The slight differences in resonant frequency and wavelength between the silver (Ag) and aluminum (Al) patches can be attributed to their distinct electronic and crystallographic structures. Silver, with its [Kr] $4d^{10}$ $5s^{1}$ configuration and highly conductive FCC lattice, supports freer electron motion, resulting in marginally higher resonant frequency and shorter wavelength. In contrast, aluminum's [Ne] $3s^{2}$ $3p^{1}$ configuration and lower electron density lead to slightly greater energy losses and a longer wavelength. Despite these structural differences, both metals maintain nearly identical VSWR, return loss, and radiated power values, indicating that their FCC metallic bonding ensures comparable electromagnetic performance with only minimal signal variation.

The graphs illustrating the relationship between the resonant frequency and return loss of the microstrip dipole antenna for the silver and aluminum materials are shown in Figures 2 and 3, respectively.

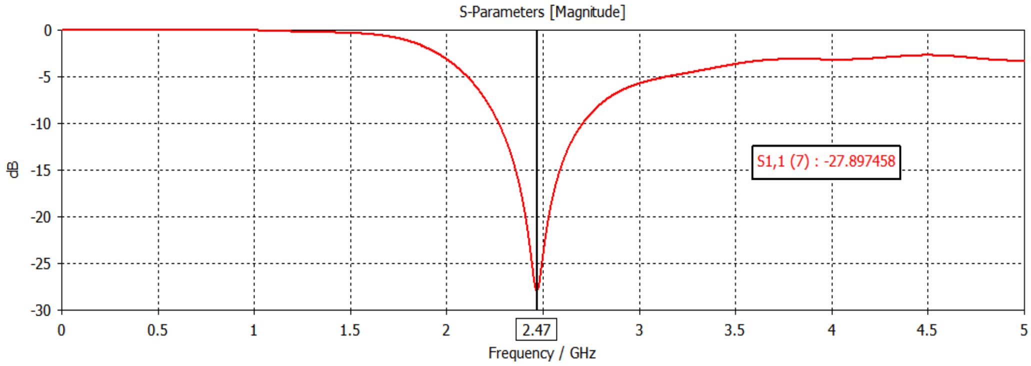

Figure 2. The graphs illustrating the relationship between the resonant frequency and return loss of the microstrip dipole antenna for the Silver (Al)

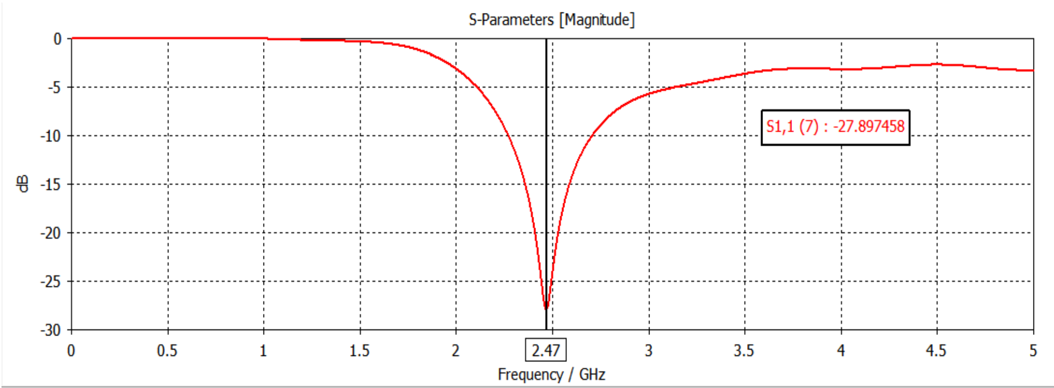

Figure 3. The graphs illustrating the relationship between the resonant frequency and return loss of the microstrip dipole antenna for the Aluminum (Al)

The Voltage Standing Wave Ratio (VSWR) values for both antennas are almost identical 1.0839 for silver and 1.0836 for aluminum indicating excellent impedance matching at the resonant frequency. Correspondingly, the reflection coefficients are low 0.0403 for Ag and 0.0401 for Al, suggesting minimal signal reflection and efficient power transfer from the feed line to the radiating element.

In terms of return loss, both antennas show very high performance with values around –27.9 dB, signifying that over 99% of the input power is successfully delivered to the antenna.

The reflected power percentages 0.162% for Ag and 0.160% for Al and mismatch losses –0.00706 dB for Ag and –0.00698 dB for Al confirm these results, further emphasizing negligible power reflection.

The forward power remains consistent at approximately 99.84% for both materials, indicating nearly total transmission efficiency. The radiated power values of 0.3647 W for silver and 0.3646 W for aluminum are also nearly equivalent, demonstrating that both conductors achieve similar radiation performance under identical design and excitation conditions.

The simulation results reveal only minor variations in the electrical characteristics of the antennas fabricated with silver (Ag) and aluminum (Al) patch materials. A small phase difference is observed, with 146.45° for Ag and 157.70° for Al, while the characteristic impedance values are 46.707 Ω and 46.396 Ω, respectively. These slight deviations can be attributed to the intrinsic electromagnetic properties and surface resistances of each metal, which slightly influence the phase distribution of surface currents across the dipole patch.

The radiation behavior of both conductors is closely linked to their crystallographic and electronic configurations. Silver possesses a face-centered cubic (FCC) lattice with a single delocalized 5s electron, enabling high charge mobility and minimal resistive losses. This structure results in slightly higher radiated power (0.3647 W) and forward power (99.837%). In contrast, aluminum, although also FCC, contains three valence electrons ($3s^2$ $3p^1$), causing stronger electron scattering and consequently a marginally lower radiated power (0.3646 W).

These findings suggest that electron density and lattice uniformity play significant roles in determining energy dissipation and radiation efficiency. Both materials, however, exhibit excellent electromagnetic compatibility, with mismatch losses below –0.007 dB, confirming efficient power transfer and impedance matching.

Overall, both Ag and Al demonstrate nearly equivalent radiation performance. While silver provides marginally higher conductivity and phase stability, aluminum offers comparable efficiency at a substantially lower cost, making it an attractive alternative for lightweight and cost-effective microstrip antenna applications.

4. CONCLUSION

The comparative analysis between silver (Ag) and aluminum (Al) patch materials for the microstrip dipole antenna demonstrates that both conductors exhibit nearly identical electromagnetic performance. The resonant frequencies of ag and al show only a negligible deviation, indicating minimal impact of material conductivity on resonance behavior. In summary, silver and aluminum yield comparable antenna performance, with silver offering slightly higher conductivity, while aluminum remains a cost-effective and practical alternative for microstrip dipole antenna fabrication without significant loss of efficiency.

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