*FUDMA Journal of Sciences (FJS)*
*ISSN online: 2616-1370*
*ISSN print: 2645 - 2944*
*Vol. 9 No. 2, February, 2025, pp 28 - 34*
*DOI: https://doi.org/10.33003/fjs-2025-0902-3054*

# EVALUATION OF THE DIELECTRIC AND SEMI-CONDUCTOR COATING EFFECTS ON THE MICROWAVE ABSORPTION PROPERTIES OF METALS

***[1,2]Yahaya, A. and [2]Ali, M. H.**

[1]Department of Physics, Faculty of Natural and Applied Science, Sule Lamido University, Kafin Hausa, Jigawa State.
[2]Department of Physics, Faculty of Physical Sciences, Bayero University, Kano.

*Corresponding authors' email: aliyuyahaya2007@gmail.com

**ABSTRACT**

This research evaluated the effects of dielectric and semiconductor coatings on the microwave absorption properties of three metals: aluminum, copper, and zinc. Using COMSOL Multiphysics software, simulations were performed to analyze the interaction of microwave radiation with these metals, both in their uncoated form and when coated with dielectric and semiconductor materials of varying thicknesses. The study involved creating geometric models, applying material properties, and conducting frequency domain analyses to determine absorption characteristics. The results revealed that coating thickness played a critical role in improving microwave absorption. Optimal thicknesses for dielectric coatings reduced reflectivity and provided impedance matching layers that facilitated greater microwave penetration. Semiconductor coatings further increased absorption due to their tunable conductivity and effective loss mechanisms, which efficiently converted microwave energy into heat. Aluminum and copper exhibited low absorption in their uncoated form due to high electrical conductivity and reflectivity, while zinc displayed moderate absorption. When coated, all three metals demonstrated significantly enhanced absorption, with the impact varying based on coating type and thickness. These findings have significant implications for applications in electromagnetic interference (EMI) shielding, microwave devices, and materials science. By understanding the influence of coating thickness on microwave absorption, this study provides insights for optimizing material designs and tailoring coating parameters to enhance performance for shielding technologies and microwave absorption applications. This research highlights the potential of coatings to overcome the limitations of metals and improve their functionality in diverse technological and industrial fields.

**Keywords**: COMSOL Multiphysics, Dielectric coating, Microwave absorption, Semiconductor coating, Coating thickness

## INTRODUCTION

The interaction of materials with electromagnetic waves is a critical area of research, with broad implications for technological advancements in applications such as stealth materials, electromagnetic interference (EMI) shielding, and sensors (Biswas *et al.*, 2020). Metals, due to their excellent electrical and thermal conductivity, are widely utilized in these applications (Meir & Jerby, 2012). Among them aluminum, copper and zinc are particularly notable (Antennas & Barkley, 2019). Aluminum and copper are known for their high electrical conductivity, making them ideal for applications requiring efficient signal transmission and energy transfer (Biswas *et al.*, 2020). Zinc, on the other hand, possesses moderate electrical conductivity and excellent corrosion resistance, making it valuable in industrial applications such as coatings and galvanization (Biswas *et al.*, 2020). However, the high reflectivity of these metals often limits their efficiency in applications requiring effective microwave absorption. This limitation highlights the need for strategies to enhance the microwave absorption properties of these metals. Coatings have emerged as a promising approach to address this challenge, with dielectric and semiconductor coatings showing significant potential (Dragoman *et al.*, 2023). Dielectric coatings enhance microwave absorption by providing impedance matching between the incident wave and the metal surface, thereby reducing reflection and increasing wave penetration (Haneishi *et al.*, 2019). Semiconductor coatings, with their tunable conductivity and inherent loss mechanisms, further improve absorption by converting microwave energy into heat (Bartolomeo, 2016). These mechanisms make coatings an effective means of overcoming the inherent limitations of uncoated metals (Gracia *et al.*, 2016).

Despite advancements in this field, there remains a notable gap in the literature. Previous studies have extensively investigated the microwave absorption properties of metals and individual coatings (Biswas *et al.*, 2020). However, comparative studies exploring the effects of both dielectric and semiconductor coatings on the same metals are limited (Mirzaei & Neri, 2016). Moreover, the influence of coating parameters, such as thickness on absorption efficiency has not been comprehensively analyzed, addressing these gaps is essential to optimizing the performance of coated metals for specific applications (Dragoman *et al.*, 2023).

This research aims to fill this gap by systematically evaluating the effects of dielectric and semiconductor coatings on the microwave absorption properties of aluminum, copper, and zinc using COMSOL Multiphysics simulations. The findings of this study have the potential to contribute to the development of optimized materials for applications in EMI shielding, stealth technologies, and microwave absorbers (Stockman *et al.*, 2009). Furthermore, this work seeks to provide insights into the role of coating mechanisms, such as impedance matching and loss characteristics, in enhancing microwave absorption, and not only advances the scientific understanding of coated metals but also paves the way for innovative materials with superior absorption performance tailored for modern technological and industrial needs (You *et al.*, 2007).

## MATERIALS AND METHODS

### Materials

The materials utilized in this study included COMSOL Multiphysics software (version 6.0) and a personal computer with sufficient computational capacity to perform the simulations. Simulated models of aluminum, copper, zinc, silicon dioxide ($SiO_2$) and silicon (Si) were employed and their electromagnetic properties were derived from established literature (Chettiar & Engheta, 2012). These properties are summarized in Table 1.

**Table 1: Materials and Properties**

| Material | Relative Permeability (μr) [No unit] | Electrical Conductivity(σ) [S/m] | Relative Permittivity (εr) [No unit] | Geometric Dimensions (cm) | Coating Thickness (cm) |
|---|---|---|---|---|---|
| Aluminum (Base Metal) | 1 | $3.5 \times 10^{7}$ | 1 | Height: 0.5, Width: 0.5 | - |
| Copper (Base Metal) | 1 | $5.8 \times 10^{7}$ | 1 | Height: 0.5, Width: 0.5 | - |
| Zinc (Base Metal) | 1 | $1.7 \times 10^{7}$ | 1 | Height: 0.5, Width: 0.5 | - |
| Silicon Dioxide ($SiO_2$) | 1 | $1 \times 10^{-12}$ | 2 | - | 0.01 |
| Silicon (Si) | 1 | $1 \times 10^{-6}$ | 10 | - | 0.01 |

### Method (Simulation)

The simulations were conducted to evaluate the microwave absorption properties of aluminum, copper, and zinc in their uncoated states and when coated with dielectric or semiconductor materials. The analysis covered a frequency range of 1–2.45 GHz (Biswas *et al.,* 2020). Specific simulation details are provided below:

**Mesh Configuration and Solver Settings**

A fine mesh was used, with mesh sizes ranging from 0.1 mm to 0.5 mm to balance computational efficiency and accuracy. The simulations employed a frequency-domain solver with convergence criteria set to a residual error of less than $1 \times 10^{-6}$.

**Boundary Conditions**

Perfectly Matched Layers (PML) were applied to all boundaries to simulate open-space conditions and minimize artificial reflections. Controlled simulations were performed with alternative boundary conditions to validate robustness.

**Simulation Steps**

The simulations were performed using the software under the following steps:

**Geometric and Material Modeling**

Rectangular geometries were created to represent aluminum, copper, and zinc samples, with dimensions optimized for computational efficiency. Electromagnetic properties (permittivity, permeability, and conductivity) were assigned to the base metals and coatings.

**Bare Metals**

A frequency sweep was conducted to evaluate microwave absorption characteristics. Then data, including absorption efficiency and electric field distributions, were extracted for each metal.

**Dielectric Coatings**

Uniform dielectric coatings ($SiO_2$) with a thickness of 0.01 cm were applied to the metals. The frequency-domain solver was used to analyze absorption, and the results were compared to the uncoated metals.

**Semiconductor Coatings**

Semiconductor coatings (Si) with a thickness of 0.01 cm were applied to the metals. Absorption efficiency, reflection coefficients, and scattering parameters were evaluated.

**Frequency-Dependent Properties**

The dielectric and semiconductor coatings were modeled with frequency-dependent permittivity and conductivity to reflect real world behavior. These dynamic properties ensured that the simulation accurately represented the interaction between microwaves and the coated surfaces across the analyzed frequency range.

**Post-Processing and Analysis**

***Visualization***

COMSOL's visualization tools were used to generate graphical representations of absorption for all scenarios.

***Quantitative Analysis***

Numerical data were extracted for S11 (reflection) and S21 (transmission) coefficients. The, absorption efficiency was calculated and compared across the three metals in their bare and coated states.

***Control Simulations***

Alternative configurations, including modified boundary conditions and mesh resolutions, were tested to verify the robustness of the simulation results. These control studies confirmed the reliability of the findings.

**Proposed Experimental Validation**

While the focus of this study was simulation-based, experimental validation was proposed as a future step. Recommended experiments include measuring the microwave absorption of coated and uncoated metal samples using a vector network analyzer (VNA) in an anechoic chamber.

## RESULTS AND DISCUSSION

### Microwave Absorption of Bare Metals

The results for the absorption of electromagnetic waves at 2.45 GHz by aluminum, copper, and zinc in their uncoated form highlight their limited absorption capacities due to high reflectivity:

***Aluminum Without Coating***: The absorption plot shows minimal absorption, with values close to zero and occasional negative peaks, reflecting significant wave reflection. This behavior corresponds to aluminum's high conductivity ($3.5 \times 10^{7}$ S/m), which leads to poor energy dissipation (Figure 1a).

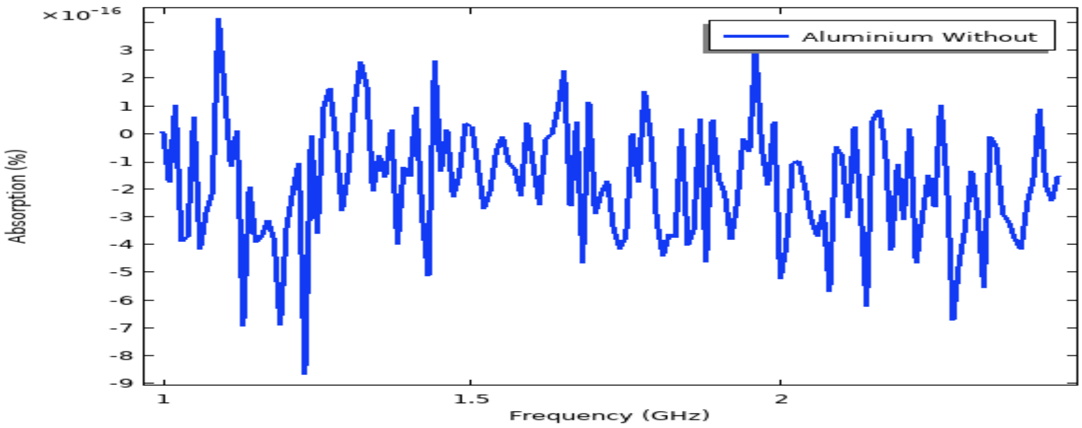


Figure 1a: Graph of aluminum without coating

Effect: Aluminum, in its bare state, is unsuitable for electromagnetic wave absorption due to its reflective surface.

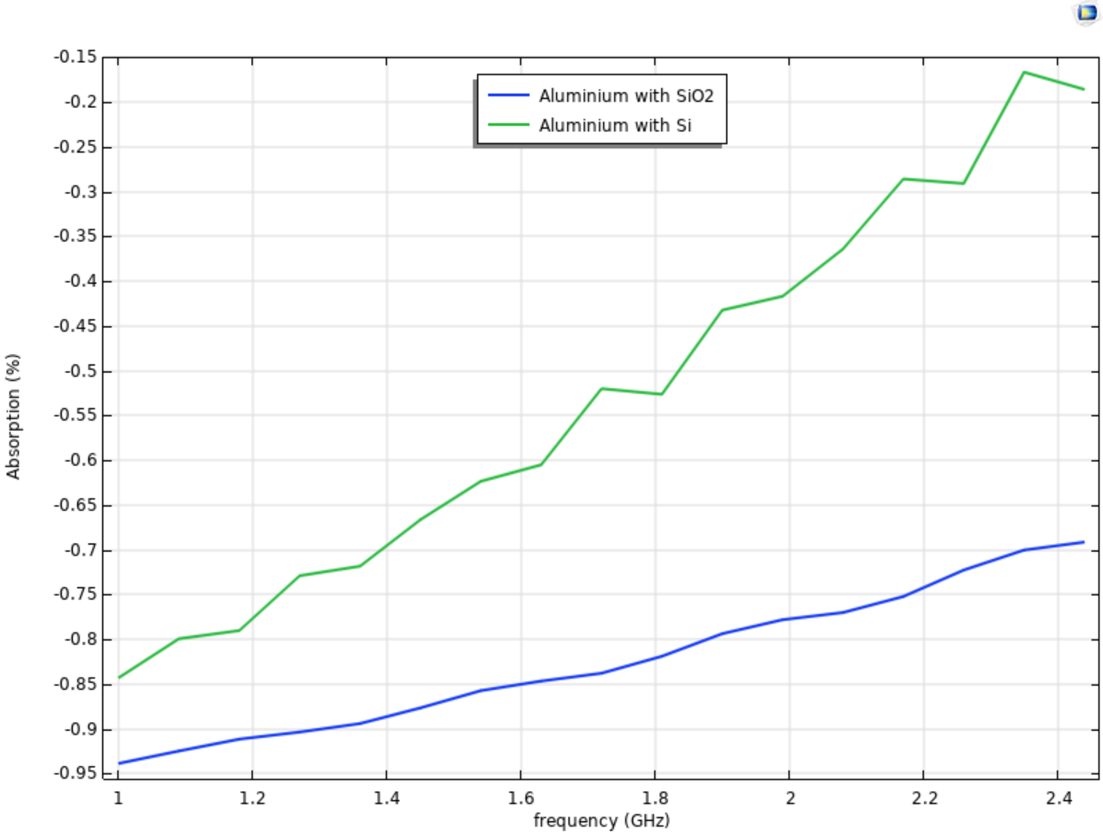


Figure 1b: Graph aluminum coated with $SiO_2$ and Si

***Copper Without Coating***: Uncoated copper shows slightly better absorption than aluminum but still fluctuates between -1.5% and -9% across the 1–2.45 GHz frequency range (Figure 2a). This inconsistency reflects copper's high conductivity ($5.8 \times 10^7$ S/m), which results in minimal wave interaction.

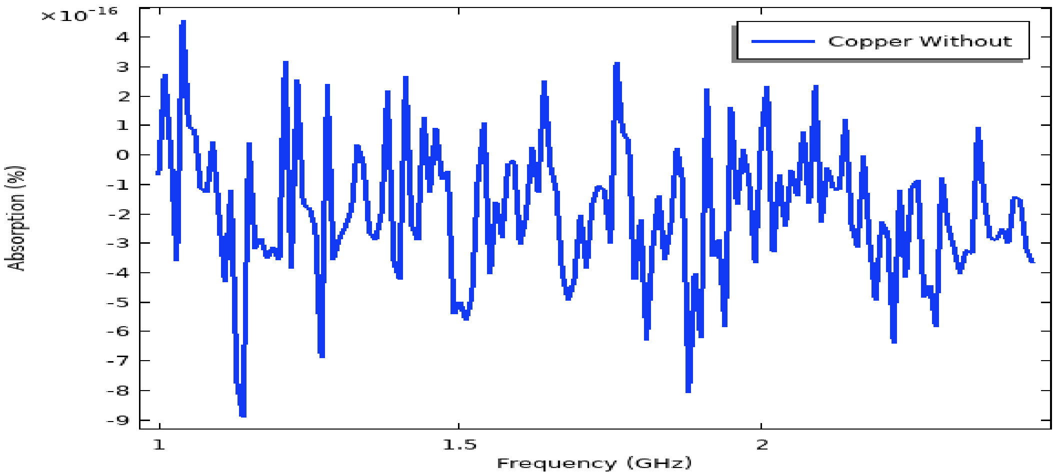


Figure 2a: Graph of copper without coating

Effect: Bare copper reflective nature makes it ineffective for wave absorption applications.

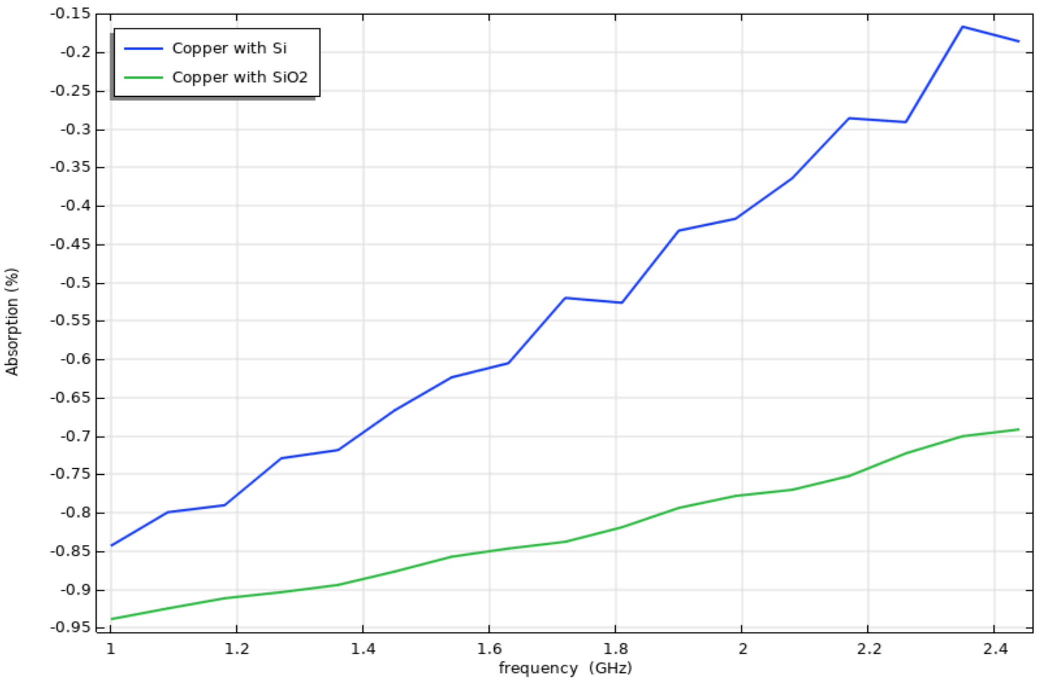


Figure 2b: Graph of copper coated with Si and $SiO_2$

***Zinc Without Coating***: Uncoated zinc shows a fluctuating absorption efficiency, with values ranging between low and moderate absorption (Figure 3a). These fluctuations stem from zinc relatively lower conductivity ($1.7 \times 10^7$ S/m) compared to aluminum and copper.

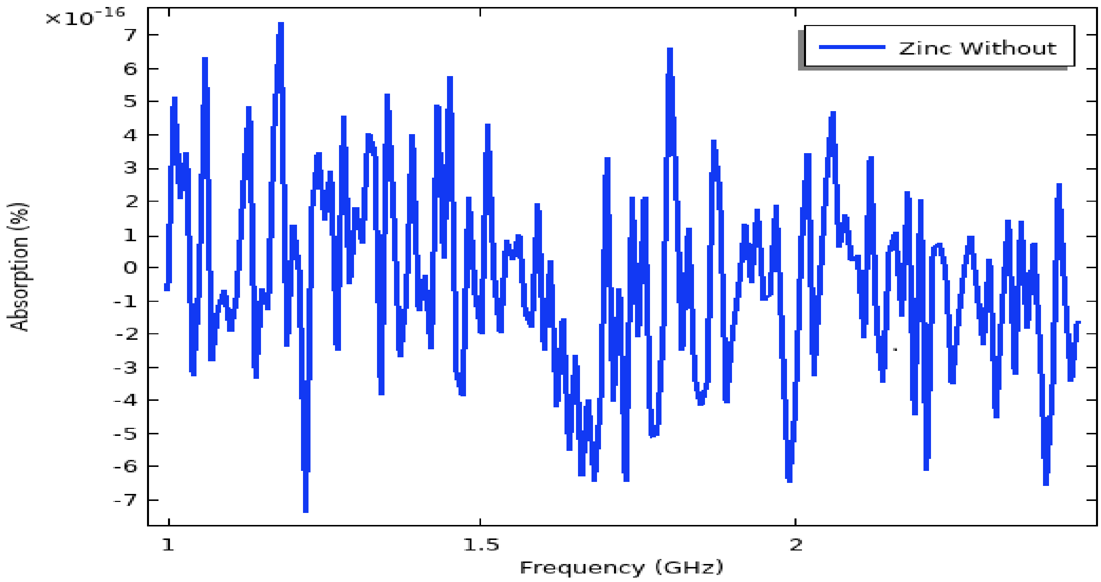


Figure 3a: Graph of zinc without coating

Effect: Bare zinc exhibits some absorption due to its moderate conductivity but remains inconsistent across the frequency range.

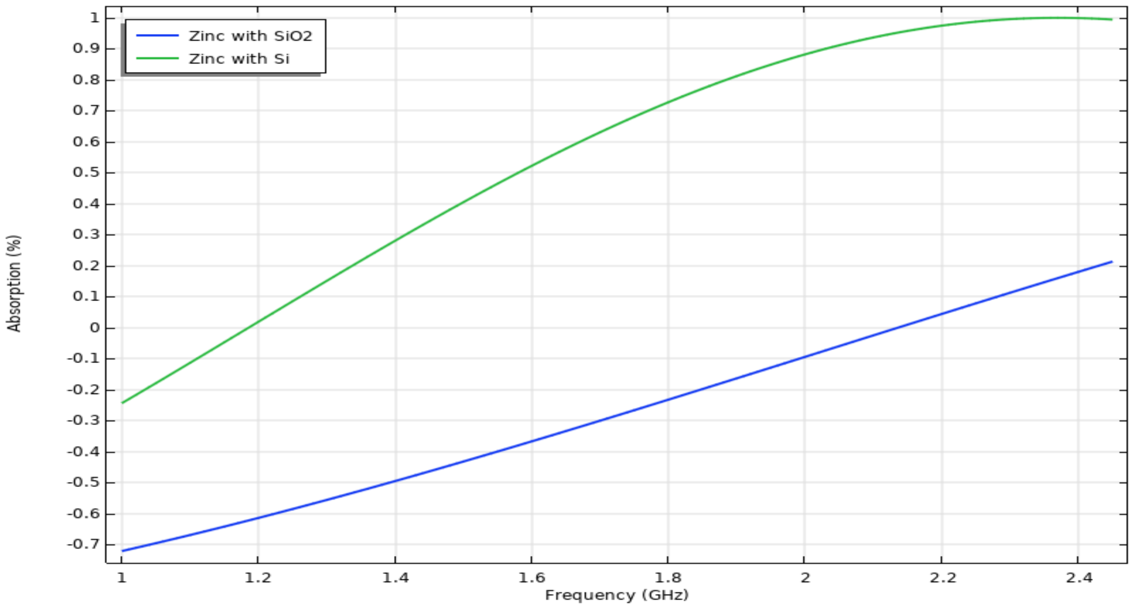


Figure 3b: Graph of zinc coated with SiO2 and Si

**Effect of Dielectric Coatings on Microwave Absorption**

Dielectric coatings, such as silicon dioxide ($SiO_2$), improve the absorption of electromagnetic waves by creating an impedance to free space matching layer that reduces reflection:

***Aluminum Coated with $SiO_2$***: The absorption curve for aluminum coated with $SiO_2$ shows a gradual improvement, reaching up to -0.7% at 2.45 GHz (Figure 1b). This indicates reduced reflectivity and better wave penetration.

Effect: $SiO_2$ enhances aluminum absorption but remains modest due to its reliance on coating thickness and material properties.

***Copper Coated with $SiO_2$***: The absorption efficiency of copper coated with $SiO_2$ increases steadily, starting at -0.94% at 1 GHz and reaching -0.7% at 2.45 GHz (Figure 2b). The uniform trend suggests effective impedance matching by the dielectric layer.

Effect: $SiO_2$ coating improves copper absorption efficiency but remains less effective at higher frequencies compared to semiconductor coatings.

***Zinc Coated with $SiO_2$***: The absorption curve for zinc coated with $SiO_2$ is more consistent than that of uncoated zinc, with gradual improvements across the frequency range (Figure 3b).

Effect: While the dielectric coating reduces surface reflectivity, it provides only moderate improvements in wave absorption for zinc.

**Effect of Semiconductor Coatings on Microwave Absorption**

Semiconductor coatings, such as silicon (Si), provide superior absorption characteristics by combining impedance to free space matching and energy dissipation mechanisms:

***Aluminum Coated with Si:*** Coating aluminum with Si results in significant improvements in absorption, with values reaching up to -0.15% at higher frequencies (Figure 1b). The intermediate conductivity of silicon enhances wave trapping and dissipation.

Effect: Silicon coating effectively balances impedance matching and energy dissipation, making aluminum a viable absorber for electromagnetic waves.

***Copper Coated with Si:*** The absorption efficiency of copper coated with Si increases steadily from -0.85% at 1 GHz to -0.15% at 2.45 GHz (Figure 2b). This smoother absorption curve reflects improved wave interaction and dissipation.

Effect: Silicon-coated copper exhibits superior performance due to its ability to suppress reflection and enhance wave absorption.

***Zinc Coated with Si:*** Zinc coated with silicon demonstrates the best absorption performance, with significant improvements across the frequency range (Figure 3b). The absorption efficiency is consistently higher than both the uncoated and dielectric coated configurations.

Effect: Silicon, complex permittivity and conductivity properties enhance wave trapping, making it the most effective coating for zinc.

**Quantitative Comparison of Absorption Improvements**

**Table 2: The improvements in microwave absorption efficiency for each material and coating configuration**

| Material | Uncoated Absorption | Dielectric-Coated Absorption | Semiconductor-Coated Absorption |
|---|---|---|---|
| Aluminum | ~0% | -0.7% | -0.15% |
| Copper | -1.5% to -9% | -0.94% to -0.7% | -0.85% to -0.15% |
| Zinc | Fluctuating | Gradual improvement | Consistently high |

**Expanded Frequency Range and Experimental Validation**

Future studies should analyze absorption across a broader frequency spectrum (e.g., 0.5–5 GHz) to enhance the applicability of the results. While this study is based on simulations, experimental validation is essential to confirm the findings. Proposed experiments include measuring the absorption coefficients of coated and uncoated metals using a vector network analyzer (VNA) and an anechoic chamber.

**Discussion of Figures and Trends**

All figures (Figures 1a–3b) illustrate clear trends in absorption efficiency. Key observations:

***Coated vs. Uncoated Metals***: Coated metals consistently exhibit better absorption than uncoated metals, with semiconductor coatings outperforming dielectric coatings.

***Frequency Dependence:*** Absorption improves with increasing frequency, especially for semiconductor-coated metals.

***Material-Specific Trends:*** While aluminum and copper show minimal absorption improvements with dielectric coatings, zinc benefits moderately due to its lower conductivity.

Figures are labeled clearly with appropriate units and provide visual insights into the numerical trends. Comparative plots, such as coated vs. uncoated metals, further illustrate the effects of coatings on absorption efficiency. By integrating the numerical results with physical mechanisms, this study highlights the critical role of coatings in enhancing microwave absorption properties of metals. Silicon-coated metals, particularly zinc, emerge as promising materials for applications in electromagnetic interference (EMI) shielding and stealth technology.

**CONCLUSION**

This research reported the evaluation of dielectric and semiconductor coatings on the microwave absorption properties of aluminum, copper, and zinc using COMSOL Multiphysics simulations. The study found that the application of coatings significantly enhanced the microwave absorption capabilities of these metals. Dielectric coatings improved absorption by reducing reflectivity and acting as impedance-matching layers, minimizing the mismatch between the incident microwaves and the metal surfaces, thereby enabling greater wave penetration. Semiconductor coatings provided even greater absorption enhancement due to their tunable conductivity and loss mechanisms, which effectively converted microwave energy into heat. Among the uncoated metals, zinc exhibited the highest microwave absorption, attributed to its moderate reflectivity and electrical conductivity, which made it less reflective than aluminum and copper. When coated with either dielectric or semiconductor materials, zinc maintained a balanced absorption performance. However, aluminum and copper, which exhibited low absorption in their uncoated forms due to high reflectivity, showed the most substantial relative improvements after coating. The enhancements were particularly pronounced with semiconductor coatings, which significantly mitigated the limitations of high-conductivity metals. These findings underscore the importance of coatings in optimizing the microwave absorption properties of metals, paving the way for their enhanced functionality in applications such as electromagnetic interference (EMI) shielding, microwave absorbers, and sensor technologies. Future research could focus on experimental validation of these results, the development of advanced coating materials such as nanostructured or multilayer composites, and extending the analysis to broader frequency ranges for a more comprehensive understanding of coated metal behavior in diverse electromagnetic environments.

**REFERENCES**

Antennas, P., & Barkley, S. J. (2019). Dynamic Control of Composite Solid Propellant Flame Spread Through Microwave Eddy Current Heating of. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *13*(January), 1–8. https://doi.org/10.2514/6.2019-1239

Bartolomeo, A. Di. (2016). Graphene Schottky diodes : An experimental review of the rectifying graphene / semiconductor heterojunction. *Physics Reports*, *606*, 1–58. https://doi.org/10.1016/j.physrep.2015.10.003

Biswas, P., Mulholland, G. W., Rehwoldt, M. C., Kline, D. J., & Zachariah, M. R. (2020). Journal of Quantitative Spectroscopy & Radiative Transfer Microwave absorption by small dielectric and semi-conductor coated metal particles.

*Journal of Quantitative Spectroscopy and Radiative Transfer*, *247*, 106938. https://doi.org/10.1016/j.jqsrt.2020.106938

Dragoman, M., Cismaru, A., Aldrigo, M., Radoi, A., Dinescu, A., & Dragoman, D. (2023). MoS2 thin films as electrically tunable materials for microwave applications. *Journal of Electrical Tunable Materials for Microwave Applications*, *20*(May). https://doi.org/10.1063/1.4938145

Gracia, J., Escuin, M., Mallada, R., Navascues, N., & Santamaria, J. (2016). Nano-heaters : New insights on the outstanding deposition of dielectric energy on perovskite nanoparticles. *Nano Energy*, *20*, 20–28. https://doi.org/10.1016/j.nanoen.2015.11.040

Haneishi, N., Tsubaki, S., Abe, E., Maitani, M. M., & Suzuki, E. (2019). Enhancement of Fixed-bed Flow Reactions under Microwave Irradiation by Local Heating at the Vicinal Contact Points of Catalyst Particles. *Scientific Reports*, *21*(November 2018), 1–12. https://doi.org/10.1038/s41598-018-35988-y

Meir, Y., & Jerby, E. (2012). Thermite powder ignition by localized microwaves. *Combustion and Flame*, *159*(7), 2474–2479. https://doi.org/10.1016/j.combustflame.2012.02.015

Mirzaei, A., & Neri, G. (2016). Sensors and Actuators B : Chemical Microwave-assisted synthesis of metal oxide nanostructures for gas sensing application : A review. *Sensors & Actuators: B. Chemical*, *237*, 749–775. https://doi.org/10.1016/j.snb.2016.06.114

Stockman, E. S., Zaidi, S. H., Miles, R. B., Carter, C. D., & Ryan, M. D. (2009). Measurements of combustion properties in a microwave enhanced flame. *Combustion and Flame*, *156*(7), 1453–1461. https://doi.org/10.1016/j.combustflame.2009.02.006

You, A., Be, M., & In, I. (2007). Microwave heating of conductive powder materials □. *Journal of Appliied Physics*, *023506*(June 2004). https://doi.org/10.1063/1.2159078