International Journal of Science, Technology and Management (IJSTM) ISSN (online): 2321-774X
Volume 10, Issue 1, 2023

A High-Performance Dual-band Microwave Absorber forElectromagnetic Shielding Application

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ABSTRACT

The paper presents the design and investigation of a high-performance absorber structure intended for electromagnetic shielding applications, specifically in the microwave frequency range of the electromagnetic spectrum. The absorber is designed to exhibit dual-band resonant peaks, resulting in near perfect absorption characteristics.By varying the geometrical parameters of the absorber, such as overall thickness, diameter of the rings, coupling between the rings, and periodicity, the spectral characteristics of the absorber can be modified. This allows for tailoring the absorption properties to specific frequency bands within the microwave range.The implemented absorber structure consists of three layers. The top and bottom layers are composed of gold, while a thin layer of silicon dioxide serves as the dielectric substrate between them. This tri-layered design contributes to the absorber's performance and functionality.The suggested absorber structure is characterized by its simplicity in design, making it easy to fabricate and deploy for practical applications. Furthermore, it exhibits polarization insensitivity, meaning it can absorb electromagnetic waves regardless of their polarization state. Additionally, the absorber remains effective for a wide range of incident angles, enabling its use when electromagnetic waves strike its top surface at various angles.Overall, this absorber structure offers promising attributes for electromagnetic shielding applications in the microwave frequency range, providing dual-band resonant absorption peaks and ease of fabrication and deployment.

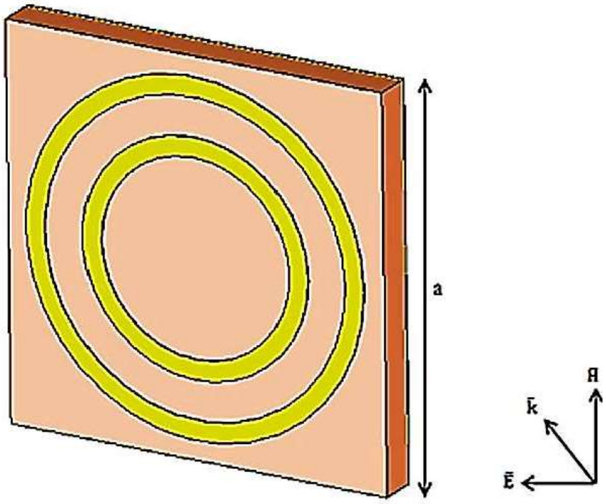
Keywords:Microwave Absorber, Metamaterial, Metamaterial, EM Shielding

INTRODUCTION

Electromagnetic absorbers, also known as electromagnetic absorbing materials or absorptive materials, have a fascinating history that spans several decades. These materials are designed to effectively absorb and dissipate electromagnetic energy, thereby reducing reflections, scattering, and unwanted electromagnetic interference. The initial work on absorbing electromagnetic energy can be traced back to the early 20th century. In the early 1930s, German physicist Gustav W. E. Mülle discovered the phenomenon of wave absorption using a mixture of graphite and a binder. This marked one of the earliest attempts to develop practical electromagnetic absorbers. During World War II, the development of radar technology led to an increased need for materials that could absorb electromagnetic waves. The British, German, and American militaries all conducted research to develop radar-absorbing materials to reduce the radar cross-section of aircraft and ships. These early absorbers were typically made of carbon-loaded rubber or carbon-based materials. The concept of stealth technology, which aims to reduce the detectability of objects by minimizing their radar, infrared, and other electromagnetic signatures, played a significant role in advancing the development of electromagnetic absorbers. In the 1970s and 1980s, various advancements were made to create stealth materials, known as radar- absorbing materials (RAM), which were integrated into stealth aircraft designs. Carbon-based absorbers have been extensively used in the development of electromagnetic absorbing materials. Materials such as carbon-loaded rubber, carbon fiber composites, and carbon foam have been employed due to their ability to dissipate electromagnetic energy effectively. The unique properties of carbon, including high electrical conductivity and low reflectivity, make it an ideal candidate for absorbing electromagnetic waves across a wide frequencyrange. In recent years, the emergence of metamaterials and frequency selective surfaces (FSS) has opened up new possibilities for electromagnetic absorption. Metamaterials are artificially engineered materials with unique properties that do not exist naturally. By manipulating their internal structure, metamaterials can exhibit extraordinary electromagnetic properties, including efficient absorption of specific frequencies. FSS, on the other hand, are periodic structures that selectively absorb or transmit electromagnetic waves at desired frequencies. Both metamaterials and FSS have shown promise in creating advanced electromagnetic absorbers with tailored absorption characteristics. Research in the field of electromagnetic absorbers continues to advance, driven by various applications such as radar and communication systems, electronic warfare, antenna design, and electromagnetic compatibility. Scientists and engineers are exploring novel materials, design techniques, and manufacturing processes to improve absorption performance, broaden the frequency range, and enhance the durability of absorptive materials. In conclusion, the history of electromagnetic absorbers spans many decades and has seen significant advancements driven by military applications, stealth technology, and the emergence of new materials and design concepts. As our understanding of electromagnetic phenomena grows, we can expect further developments in the field of absorbing materials, enabling improved electromagnetic performance across a range of applications.

DESIGN ASPECTS

The above theory gives an overview of various studies and designs related to polarization-insensitive and dual-band metamaterial absorbers. Here is a summary of the key points mentioned above:



Novel Design: The suggested construction involves a regular pattern of a ring resonator and a circular resonator on an FR4 dielectric substrate with a grounded metallic bottom. This design achieves high absorptivity at specific frequencies in the C and X bands, with 99.8% absorptivity at 5.9 GHz and 99.97% absorptivity at 9.9 GHz.

Polarization-Insensitive Behaviour: The proposed absorber exhibits polarization-insensitive behaviour for both electric and transverse magnetic polarizations under oblique and normal angles of incidence.

Absorption Mechanism and Field Distributions: The absorption mechanism and field distributions of the constructed structure have been examined to better understand its performance.

Experimental Validation: The constructed structure has been tested, and the experimental absorber's performance.

Radar Applications: Due to its straightforward construction and high absorption, the polarization-insensitive metamaterial absorber is suitable for radar applications.

IMPLEMENTATION

Here in this research work a tri-layered metamaterial absorber structure has been designed using two concentric rings of gold material at the top of the silicon -dioxide substrate which is a dielectric layer sandwiched between the top and bottom layers and behaves as a Fabry-Perot cavity to here for the absorption to take place. The bottom layer is made up of gold sheet of a thickness for hindering the transmission of electromagnetic waves out of the cavity of the absorber. The two gold rings act as a resonator here and provides good resonance peaks at two different frequencies.Due to the existence of the ground plane on the bottom layer, with thickness greater than the skin depth, the transmission through the structure can be effectively suppressed, which indicates $S21(\omega) = 0$. So, the absorption equation can be altered to the following:

$$A(\omega) = 1 - R(\omega)$$

The research work describes the design of a tri-layered metamaterial absorber structure. The structure consists of the following layers:

Top Layer: The top layer of the absorber comprises two concentric rings made of gold material. These rings act as resonators and are responsible for providing resonance peaks at two different frequencies. The specific geometry and dimensions results match the simulations, confirming the absorption characteristics.

Dielectric Layer: The dielectric layer, sandwiched between the top and bottom layers, is made of silicon dioxide (SiO_2) material. This layer serves as a dielectric spacer and behaves as a Fabry-Perot cavity. The Fabry-Perot cavity is responsible for enhancing the absorption of electromagnetic waves within the absorber structure.

Bottom Layer: The bottom layer is made of a gold sheet. It is designed to have a sufficient thickness to hinder the transmission of electromagnetic waves out of the absorber cavity. By preventing wave transmission, the gold sheet contributes to the absorption of the incident electromagnetic waves within the absorber.

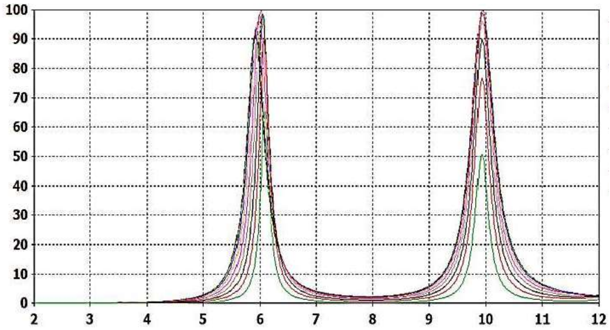


Fig. 1.1 Dual Band Response

The output current (S21|) and reflecting power (S11|), is provided by Eqn. 1.1, is used to calculate the absorptivity (A) of the absorption method when the simulations are complete. Due to the entire metal ground, the S21 becomes zero, stopping wave transmission. To create the ideal metamaterial absorber, the wave reflection should be reduced. This is accomplished by impedance matching the structure to the open space impedance. Eqn. 1.2 provides the input impedance (Z). An impedance-matched structure should have an imaginary input impedance of zero and a real input impedance of unity.

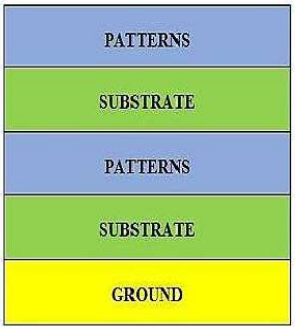


Fig. 1.2 Multi-Layer Structure

Permittivity $\varepsilon(\omega) = \varepsilon_1 + i\varepsilon_2$ and permeability$\mu(\omega) = \mu_1 + i\mu_2$ are examples of effective medium properties that define the metamaterials. These intricate effective parameters, which often relate to attenuation in a medium, are calculated using the effective medium technique.The structure with high attenuation and high absorption is built by the absorber using the loss of these characteristics and the effective medium design. The actual components of the important parameter are related to the electromagnetic wave propagation. The imaginary (loss) components are smaller than the real components. By manipulating the resonances independently in μ and ε, both the incident magnetic and electric fields could be absorbed. The effective permittivity (ε_{eff}) and effective permeability (μ_{eff}) are calculated using electric susceptibility (χ_{es}) and magnetic susceptibility (χ_{ms}), as shown in Eqn. 1.3, Eqn. 1.4, Eqn. 1.5 and Eqn. 1.6, where k_0 is the wavenumber of the free space and d is the distance travelled by the incident electromagnetic wave.

RESULT ANALYSIS

The detailed characteristics and simulation results of the proposed metamaterial absorber structure is summarized with these few key points mentioned below:

Structure Design: The absorber structure consists of a 1 mm thick dielectric FR4 substrate, which acts as a barrier between the metallic impressions and the grounded copper bottom. The upper layer comprises ring resonators in both square and circular shapes. Copper is used for the metallic layers, with a thickness of 0.035 mm.

Simulation Method: The structure is modeled using periodic boundary conditions in Simulink CST. It is excited by a Floquet port, and the transmission coefficient S21 decreases to zero when the maximum absorbance is achieved, indicating complete absorption of plane waves.

Absorption Performance: Different configurations of the absorber structure, including spherical resonators, square metamaterial absorbers, and the suggested structure combining square and circular resonators, are simulated. The absorptivity, resonant frequencies, and reflectance of each configuration are evaluated. The suggested structure achieves enhanced absorption with absorptivity of 99.8% at 5.5 GHz and 9.97% at 8.9 GHz.

Impedance Matching: The normalized impedance plot for the suggested structure demonstrates perfect impedance matching with the open space, resulting in zero reflection and a real portion of impedance closer to unity.

Surface Current Distribution: The distribution of surface current density in the top and bottom layers of the absorber is analysed. A circulating current loop is formed, and a significant portion of the surface current network is located within the outer ring, contributing to absorption at 5.5 GHz, while the inner circular resonator is responsible for absorption at 8.9 GHz.

Electromagnetic Field Reactions: The electromagnetic dispersion at dual wavelengths is depicted, showing that the magnetic flux is transverse to the circulating current loop and incident on the metallic top layer. The electromagnetic and electric fields become more pronounced at resonance frequencies, leading to increased absorption.

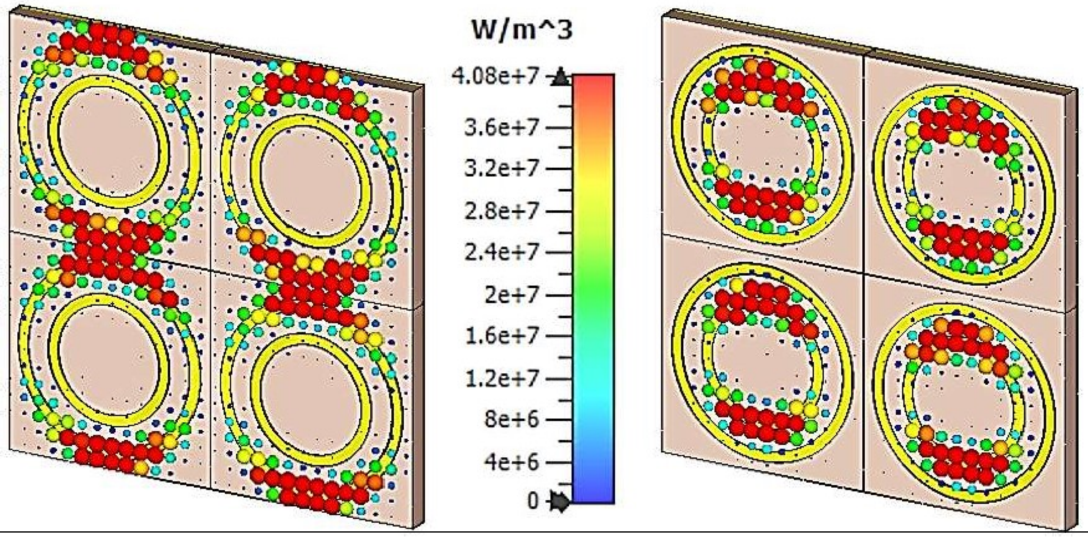


Fig.1.3 Absorber Resonant Response for both the Rings

These findings demonstrate the effectiveness of the proposed metamaterial absorber structure in achieving dual-band absorption and optimizing the electromagnetic field reactions. Gold is a commonly used material in metamaterial resonator layers for absorbers due to its unique properties. Gold exhibits strong plasmonic properties, particularly in the visible and near-infrared range. Plasmons are collective oscillations of electrons in metals, and they can be harnessed to manipulate and control electromagnetic waves. The plasmonic behaviour of gold allows for enhanced light-matter interactions and efficient absorption of electromagnetic energy. It is highly conductive, making it suitable for resonator applications. Its high electrical conductivity enables the resonator to efficiently couple with the incident electromagnetic waves, leading to strong absorption. Additionally, the low resistivity of gold minimizes ohmic losses, contributing to higher absorption efficiency. The resonant frequency of a metamaterial absorber can be tuned by adjusting the dimensions and geometry of the resonator elements. Gold's optical properties can be finely tuned by modifying the shape, size, and arrangement of the resonators, allowing for precise control over the absorption frequency or bandwidth. Gold is compatible with various fabrication techniques, including lithography and thin-film deposition methods. This enables the fabrication of complex and precise metamaterial structures with gold resonator layers. Gold's stability and ease of processing make it a preferred choice for practical implementation. Gold is highly stable and resistant to oxidation, making it suitable for long-term use in various environments. This stability ensures the longevity and durability of the metamaterial absorber, allowing it to maintain its absorption properties over time. These factors make gold a favourable choice for metamaterial resonator layers in absorbers, enabling efficient absorption of electromagnetic waves and tailoring the absorber's performance for specific applications in areas such as sensing, energy harvesting, and optical devices.

Gold can be used as a resonator material in various metamaterial applications.

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