

Parametric Study of a Microwave Absorber Based on Metamaterials.

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Abstract – Microwave absorbers play a crucial role in modern telecommunications and electronic systems by mitigating unwanted electromagnetic interference (EMI) and enhancing the performance of various devices. These absorbers are essential in applications ranging from radar systems and anechoic chambers to consumer electronics and medical devices. Traditional microwave absorbers, while effective, often suffer from limitations such as bulkiness and narrow bandwidth. Metamaterial-based microwave absorbers offer a promising alternative due to their unique electromagnetic properties, which are not found in natural materials. These engineered materials can achieve near-unity absorption across a wide range of frequencies, making them highly efficient. The advantages of metamaterial absorbers include their thin profile, lightweight nature, and the ability to tailor their absorption characteristics through precise structural design. This makes them ideal for applications requiring compact and efficient EMI mitigation. Additionally, metamaterial absorbers can be designed to operate over multiple frequency bands, providing versatility and enhanced performance in complex electromagnetic environments.

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I Introduction

The study begins with a theoretical exploration of absorber devices and the unique properties of metamaterials that make them suitable for electromagnetic wave absorption. Following this, the report details the implementation of a specific microwave absorber device using advanced simulation software, highlighting the practical aspects of device design and performance evaluation. Finally, the report addresses the parametric design and optimization of the device, fine-tuning structural parameters to achieve

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optimal absorption characteristics. Through this comprehensive approach, the report aims to provide a thorough understanding of the principles, design methodologies, and practical applications of metamaterial-based microwave absorbers.

II Theoretical Study

Metamaterials are artificially engineered materials with unique electromagnetic properties not found in nature. They are designed with specific geometrical structures that allow them to exhibit properties like negative refractive index, reverse Snell's law, and right/left-handed behavior. The first to coin the term of metamaterial absorbers was Victor Veselago [1].

An MMA typically comprises three layers:

- A periodic metallic pattern on top
- A dielectric substrate in the middle
- A bottom metallic ground plane

As multi-layer structures in MMAs enable broadband absorption by creating multiple resonant frequencies. By stacking different layers with varying properties, a wider range of frequencies can be absorbed effectively.

Impedance matching is crucial for MMAs to minimize reflection and maximize absorption. This is achieved when the impedance of the MMA is matched to the impedance of free space, ensuring that incident electromagnetic waves are absorbed rather than reflected.

In order to evaluate the absorption of the microwave metamaterial absorber proposed in this study [2] the reflection and transmission power shall be calculated as well as the reflection coefficient. The bare necessary equations are shown in (1).

$$Z = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}} \quad (1a)$$

$$\Gamma = \frac{Z - Z_0}{Z + Z_0} \quad (1b)$$

$$T = \frac{2Z_0}{Z + Z_0} \quad (1c)$$

$$A = 1 - |\Gamma|^2 - |T|^2 \quad (1d)$$

However the Impedance across the frequency range shall be normalized and in order to be calculated the impedance of each layer shall be factored in but thankfully this is done by CST.

III Simulation

The simulation was conducted using CST (Computer Simulation Technology) software to implement a configuration inspired by the design presented in [2]. This section outlines the steps taken to model the structure, the assumptions made, and the results obtained from the simulation.

III.I CST Implementation

The vertical layout in CST consists of a three-layer structure:

- **Dielectric Substrate:** This layer serves as the base for the structure.
- **Air Gap:** Positioned above the dielectric substrate, this layer introduces an air gap to influence the electromagnetic properties.

- **Metal Backplate:** The top layer, made of copper, acts as a reflective surface.

The dielectric substrate also includes a metallic component, which is made of the same material as the metal backplate—copper, with a conductivity of $(5.96 \mu\text{S/m})$.

Initially, the FR-4 substrate is placed without the metal resonance layer. The other two layers are positioned below $Z = 0$. When viewed from the orthographic side, the layout appears as shown in Figure 1.

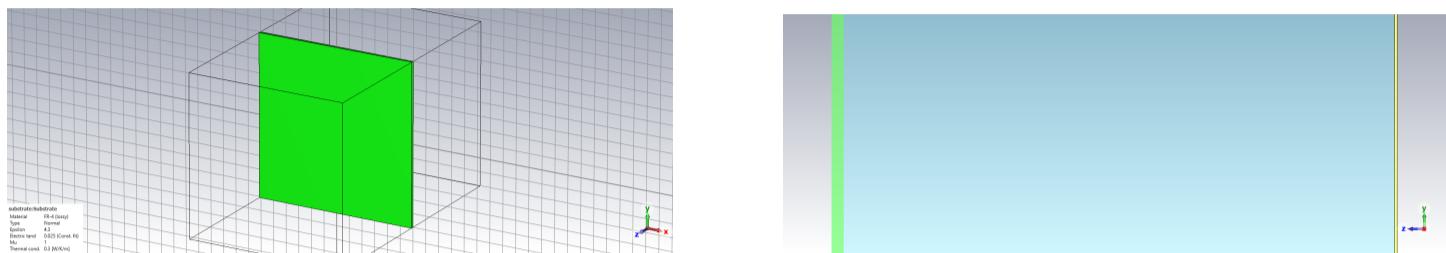


Figure 1: Basic Vertical Layout

Next, a ring resonator is added on top of the dielectric substrate. The ring is made of the same material and thickness as the backplate, as illustrated in Figure 2.

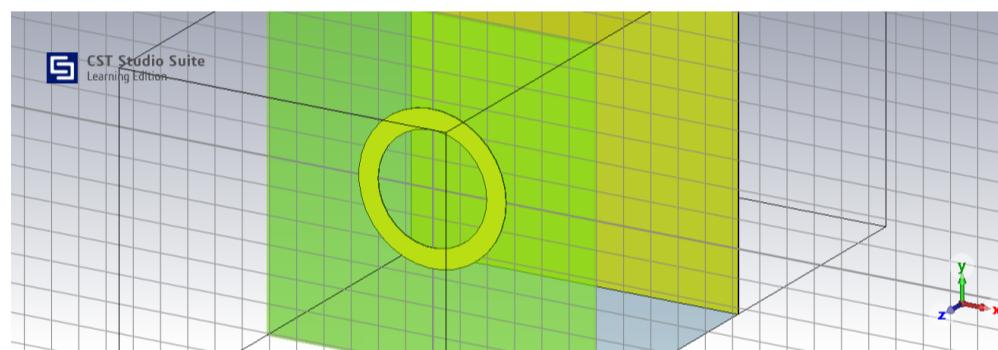


Figure 2: Ring Resonator

An important assumption in this design is that both the body and the tip of the arrow have a width of $\alpha = 0.5\text{mm}$. To accurately place the curve points defining the arrow, a system of equations must be solved to determine the Cartesian coordinates of the arrow's base points. These points lie on the arc of the ring and are equidistant from the curve $y = x$. The following MATLAB code snippet demonstrates the solution to this system:

```

1      syms x1 x2
2
3      eq1 = 2*(x1 - x2)^2 == .5^2; eq2 = sqrt(x2^2 + x1^2) == 2.7;
4
5      sol = solve([eq1, eq2], [x1 x2]); disp([sol.x1 sol.x2]);

```

This system simplifies to the equations shown in Equation 2.

$$\begin{pmatrix} \sigma_3 - \frac{2916\sigma_1}{1433} & -\sigma_1 \\ \sigma_4 - \frac{2916\sigma_2}{1433} & -\sigma_2 \\ \frac{2916\sigma_1}{1433} - \sigma_3 & \sigma_1 \\ \frac{2916\sigma_2}{1433} - \sigma_4 & \sigma_2 \end{pmatrix}$$

where

$$\sigma_1 = \sqrt{\frac{729}{200} - \frac{7\sqrt{59}}{80}} \quad (2)$$

$$\sigma_2 = \sqrt{\frac{7\sqrt{59}}{80} + \frac{729}{200}}$$

$$\sigma_3 = \frac{400 \left(\frac{729}{200} - \frac{7\sqrt{59}}{80} \right)^{3/2}}{1433}$$

$$\sigma_4 = \frac{400 \left(\frac{7\sqrt{59}}{80} + \frac{729}{200} \right)^{3/2}}{1433}$$

The arrow is then mirrored across the X, Y, and XY planes to cover all four sides of the cell. The face is covered with copper, and a height of $d = 0.035mm$ is assigned, as shown in Figure 3. This step is crucial because all other layers were initially positioned below $Z = 0$.

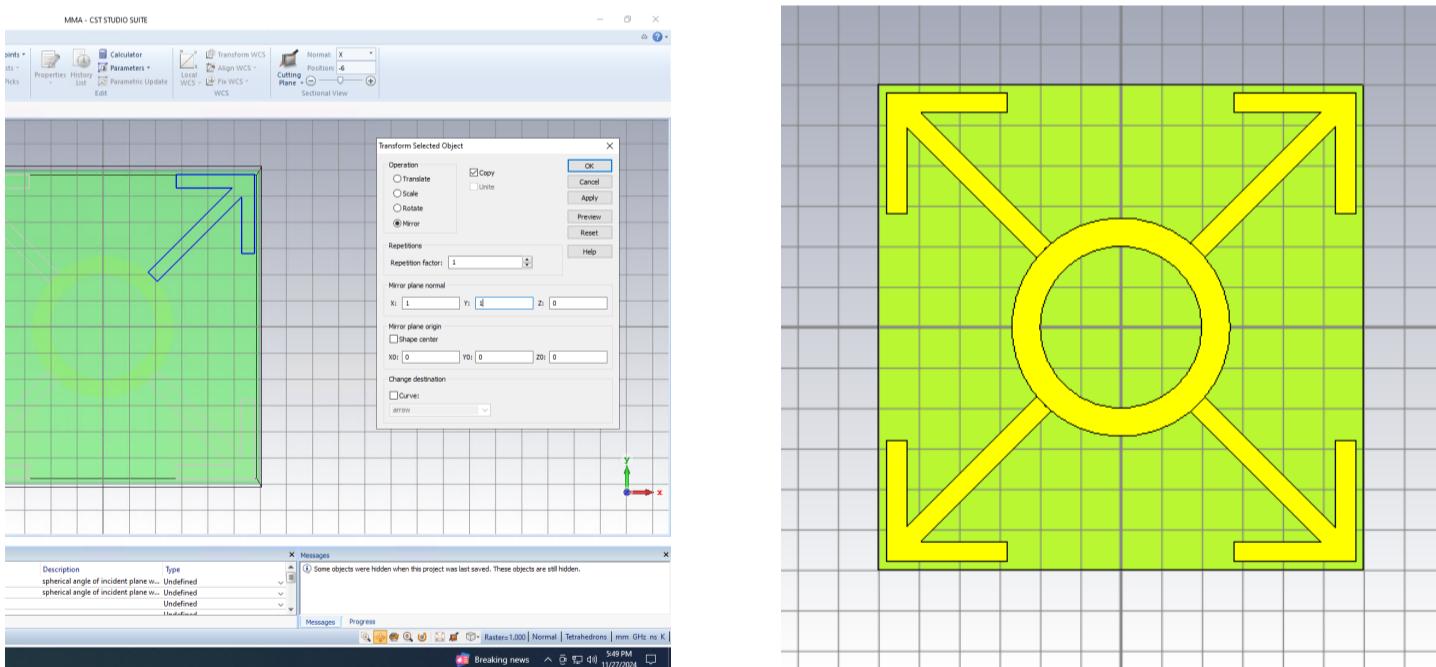


Figure 3: Mirroring Arrow and Cover

A series of cuts (boolean subtractions) are made in the resonance layer to add resistors between the copper faces near the arrows, as depicted in Figure 4.

Similar cuts are made near the ring to ensure uniform width, as shown in Figure 5.

Resistors are then added, connecting to the center points of the faces created by the previous subtractions, as illustrated in Figure 6a. It is important to note that the performance of the absorber may be reduced in this implementation. Better absorbance might be achieved if the connection height is set to $d = 0.035mm$.

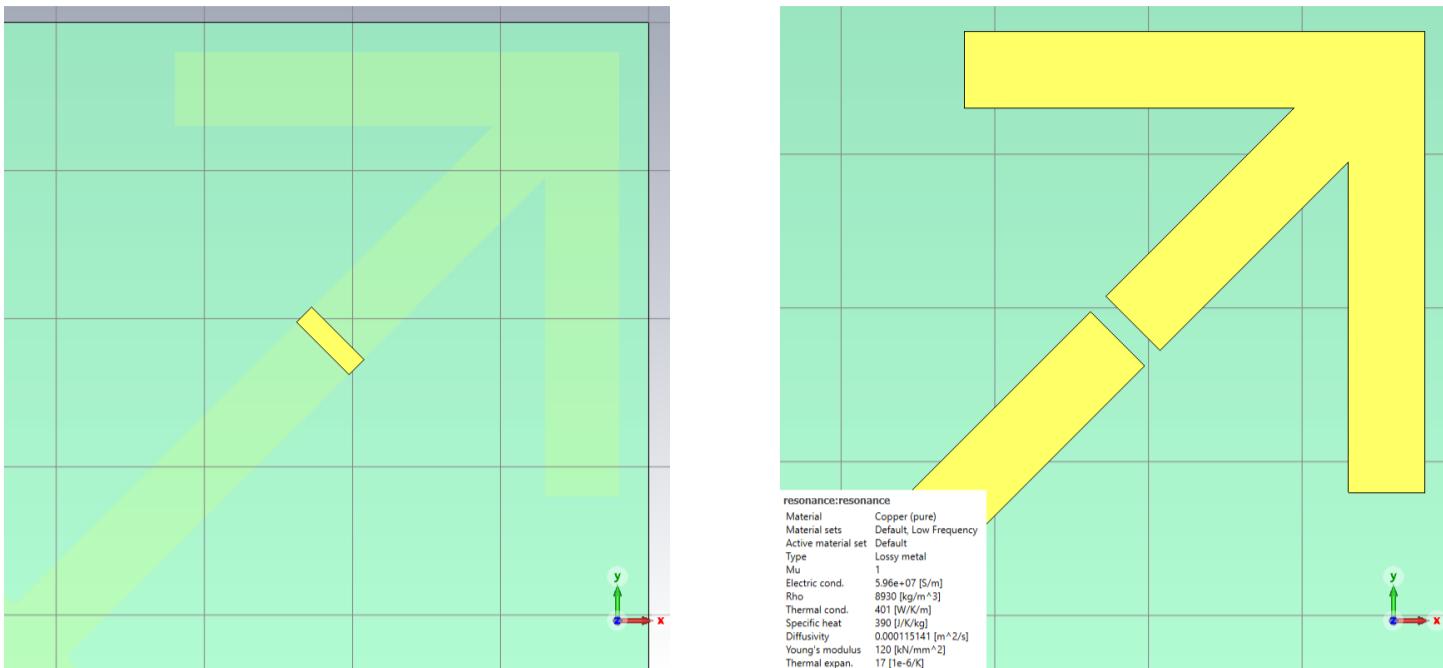


Figure 4: Cuts Near the Arrows

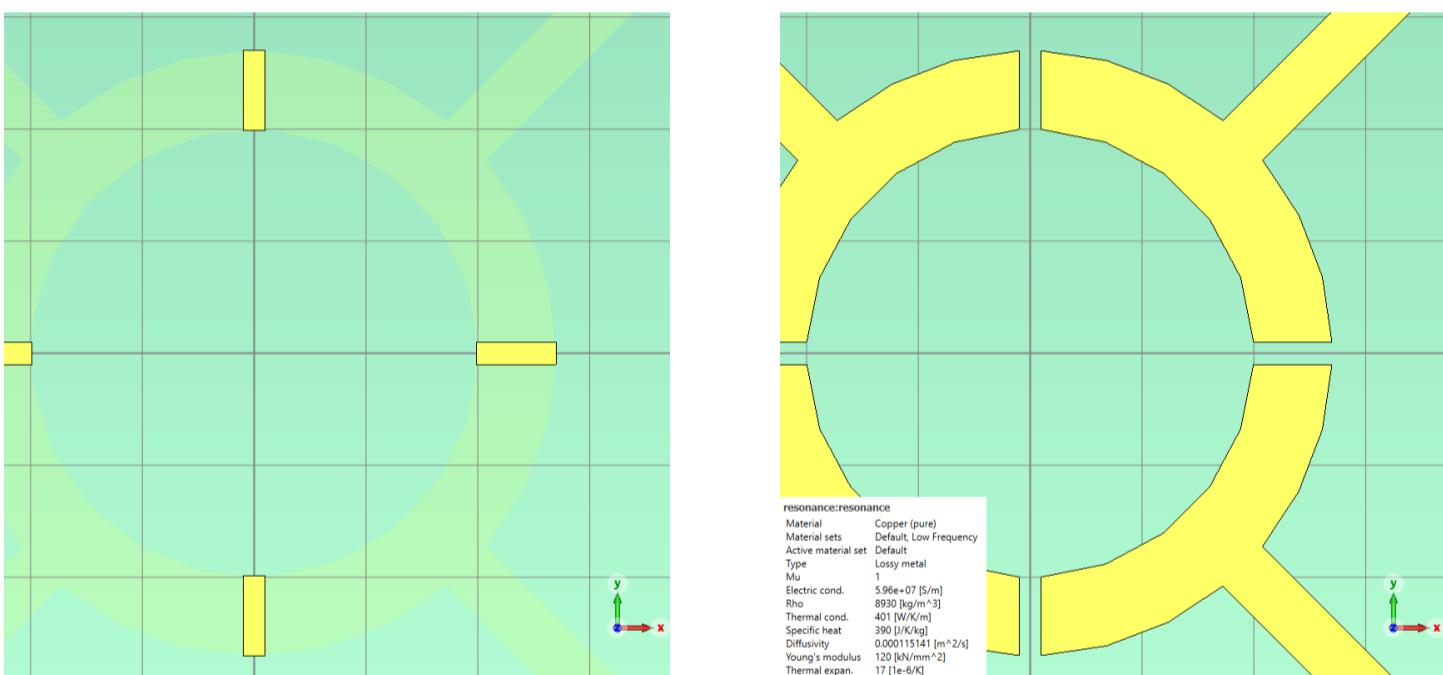


Figure 5: Cuts Near the Ring

To perform the simulation using the frequency solver in CST, periodic boundaries are set along the XY plane, and free space conditions are applied along the Z axis. The resulting mesh is shown in Figure 6b.

The electrical field absorbance is analyzed at different frequencies. Figure 7 shows the electrical field for $Z_{max}(1)$ at frequencies of 2.7 GHz, 7.7 GHz, and 12.7 GHz.

Similarly, Figure 8 shows the electrical field for $Z_{max}(2)$ at the same frequencies.

Taking a look in the S_{11} of Z_{max} after the simulation as such (III.I). The Absorptivity (against the frequency) is an essential metric and CST calculates it as shown in (III.I). For the evaluation of the absorber Absorptivity can be calculated using the formula: $A = 1 - |S_{11}|^2 - |T|^2$, where T is the transmission coefficient and can be calculated using the formula: $T = \frac{2Z_0}{Z + Z_0}$. However the Z mentioned needs to be the normalized impedance of the absorber so this is where the calculation will start.

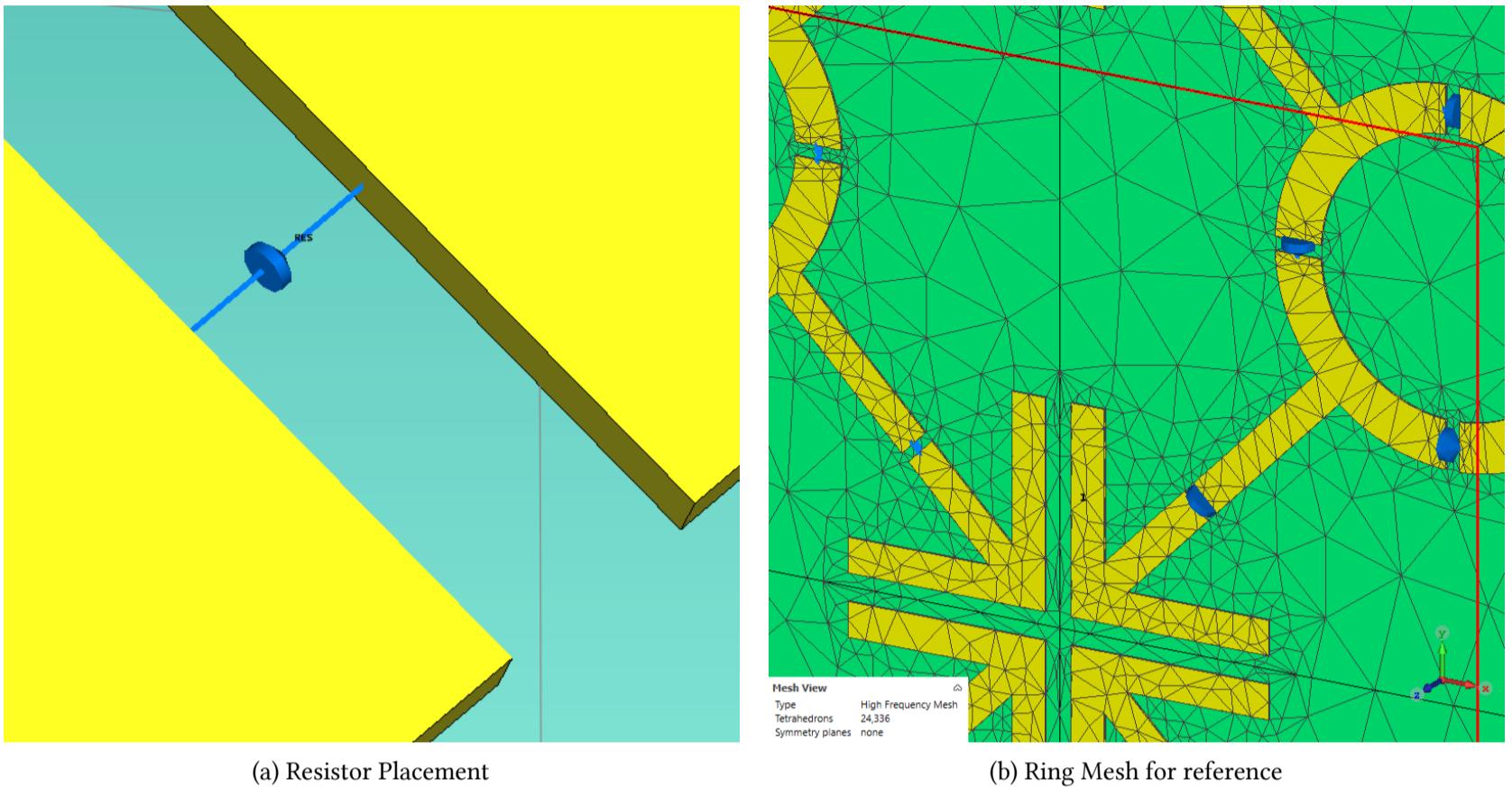


Figure 6: Mesh around Resistors

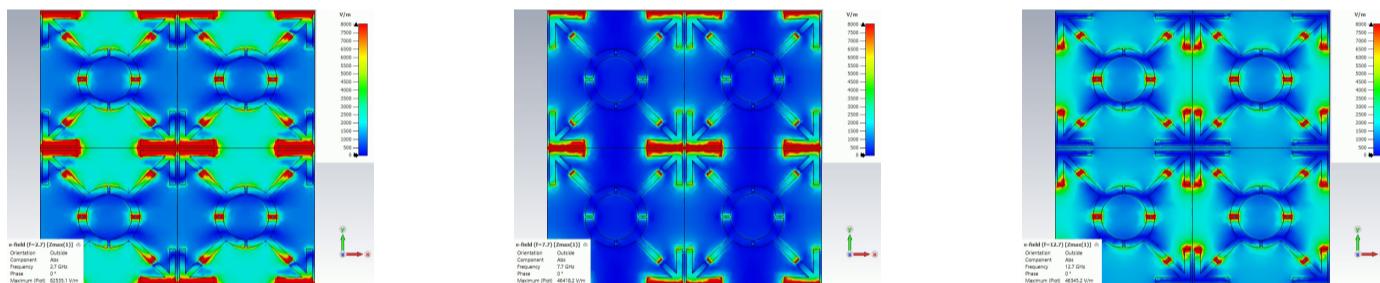
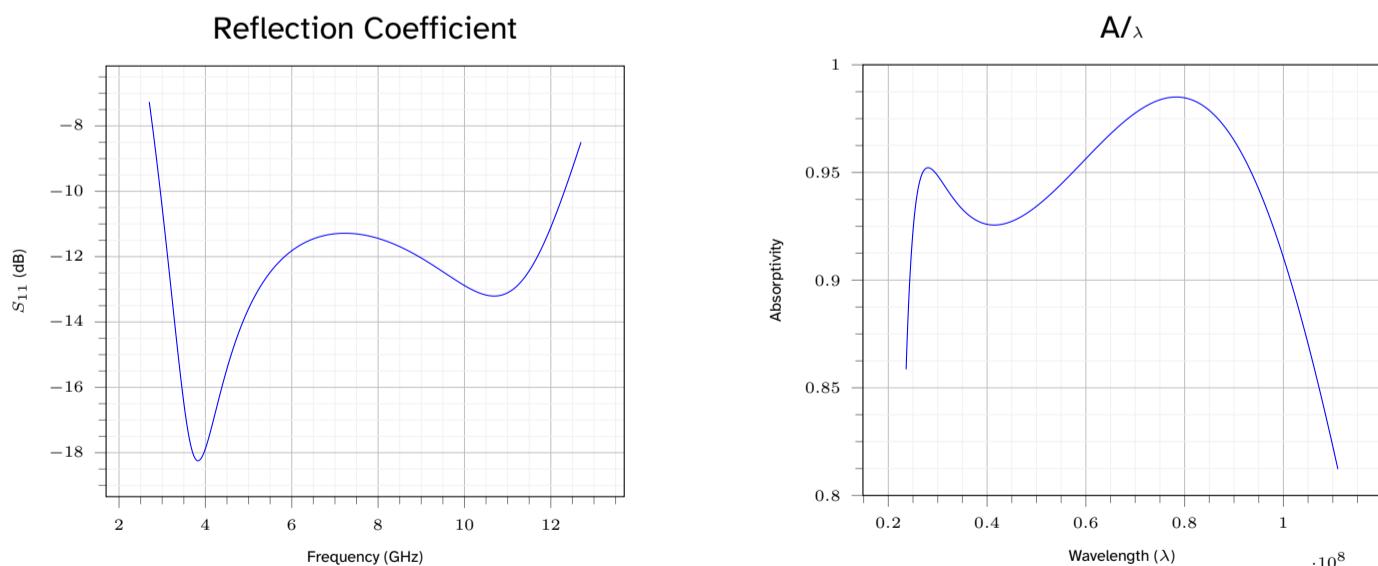


Figure 7: Electrical Field for [2.7, 7.7, 12.7] GHz $Z_{max}(1)$



The relative permittivity (ϵ) and permeability (μ) are extracted from the S_{11} and S_{12} parameters. Their imaginary parts are shown in Figure 9.

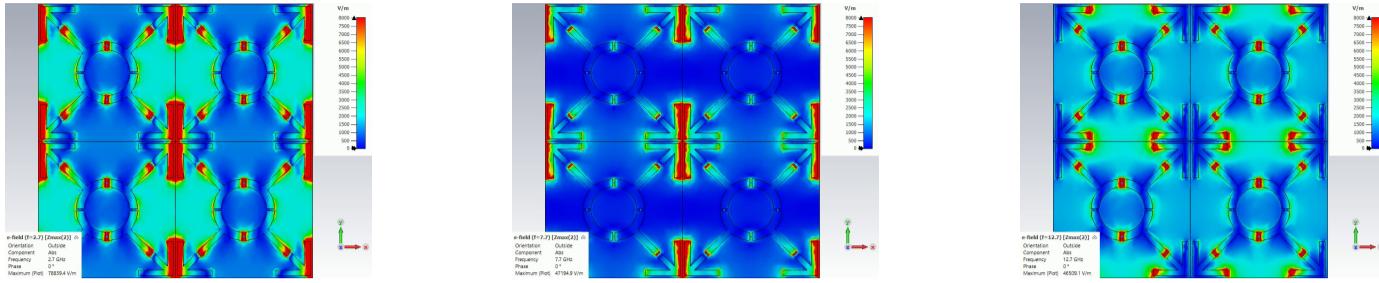


Figure 8: Electrical Field for [2.7, 7.7, 12.7] GHz $Z_{max}(2)$

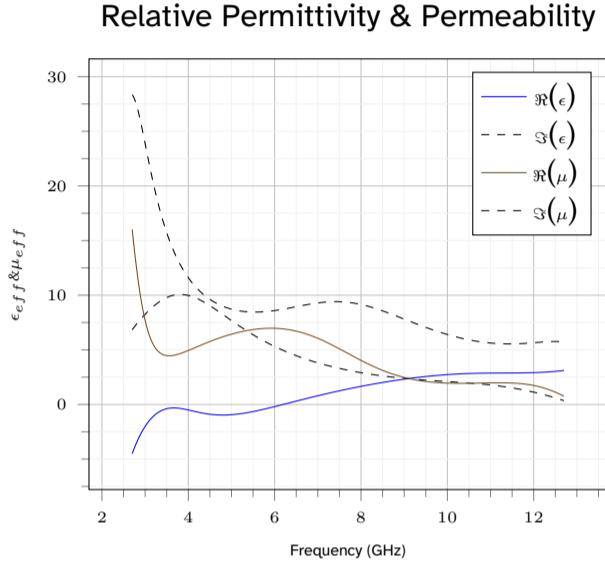


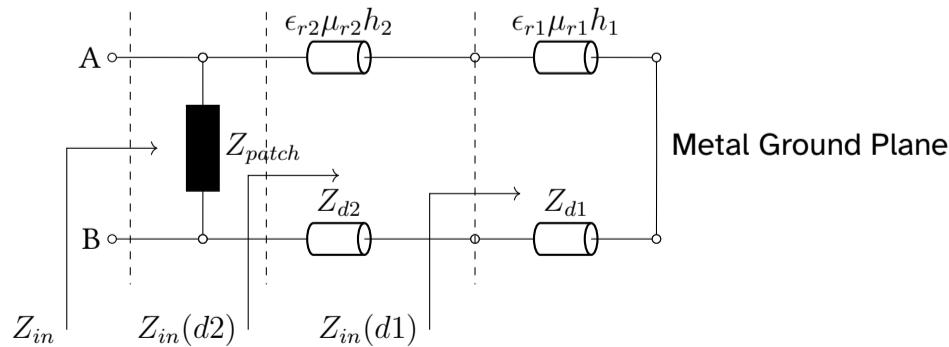
Figure 9: Effective ϵ & μ

III.II Alternative Modeling Methods

In addition to the CST simulation, there are several alternative methods to model the absorber:

- **Transmission Line Equivalent:** This method models the absorber as a transmission line, which can be useful for understanding the impedance matching and wave propagation.
- **Electrical Circuit Equivalent:** The absorber can be represented as an equivalent electrical circuit, simplifying the analysis of its behavior.
- **Mathematical Modeling & Code (MATLAB):** Numerical methods and coding in MATLAB can be used to simulate the absorber's performance, providing flexibility in parameter adjustments.

After completing the CST simulation, the impedance of the absorber can be extracted, which is useful for implementing the transmission line equivalent model. For this the Z_{patch} is extracted from CST as the behavior of the absorber is related to the quality of impedance matching of the metal resonance layer which is connected in parallel to the impedances of the FR-4 substrate and the air layer respectively. Finally the copper backplate is represented as a sort circuit.



So the entire absorber can be modeled as a simple impedance matching problem with the basic equations in (1). The objective is

for the equivalent impedance of the absorber to match the free space impedance and in order to simulate that with a transmission line equivalent the input impedances of each absorber layer shall be calculated. The input impedance of the air layer and the metal ground plane is calculated as in (3b) with the phase constant as in (3a). Then the FR-4 layer is has a relative permittivity (ϵ) of 4.3 and a relative permeability (μ) of one but in the calculations the phase constant (3f) is derived from the loss tangent (3c) because the medium is way more dense than vacuum and thus the wavelength is less than $\frac{c_0}{f}$. So the input impedance of the combined FR-4, Air and Metal ground plane is calculated as in (3h).

$$\beta_1 = \frac{2\pi\sqrt{\mu_{r1}\epsilon_{r1}}}{\lambda} \quad (3a)$$

$$Z_{in}(d_1) = jZ_{d1} \tan \beta_1 h_1 = jZ_0 \sqrt{\frac{\mu_{r1}}{\epsilon_{r1}}} \tan \frac{2\pi h_1 \sqrt{\mu_{r1}\epsilon_{r1}}}{\lambda} \quad (3b)$$

$$\tan \delta = \frac{\sigma}{\omega \epsilon} = 0.025 \ll 1 \text{ where } \delta = \frac{1}{\alpha} \quad (3c)$$

$$\alpha = \frac{\sigma}{2} \sqrt{\frac{\mu_2}{\epsilon_2}} \Rightarrow \alpha = 40 \quad (3d)$$

$$\sigma = \sqrt{\frac{\epsilon_0 \epsilon_{r2} 2\alpha}{\mu_0 \mu_{r2}}} \quad (3e)$$

$$\beta_2 = \omega \sqrt{\frac{\mu_{r2} \mu_0 \epsilon_{r2} \epsilon_0}{2}} \left[\sqrt{1 + \left(\frac{\sigma}{\omega \epsilon_{r2} \epsilon_0} \right)^2} + 1 \right]^{\frac{1}{2}} \text{ where } \omega = 2\pi f \quad (3f)$$

$$Z_{d2} = Z_0 \sqrt{\frac{\mu_{r2}}{\epsilon_{r2}}} \quad (3g)$$

$$Z_{in}(d2) = Z_{d2} \frac{Z_{in}(d_1) + jZ_{d2} \tan \beta_2 h_2}{Z_{d2} + jZ_{in}(d_1) \tan \beta_2 h_2} \quad (3h)$$

The Z_{patch} is the impedance of the metal resonance layer and is extracted from the S parameters of the simulation. In greater detail the normalized impedance (or the intrinsic impedance) z for the entire absorber is expressed as (4a). And the refractive index can be expressed as (4b) using the S parameters.

$$z = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 + S_{21}^2}} \quad (4a)$$

$$n = \frac{1}{kg} \arccos \left[\frac{1}{2S_{21}} (1 - S_{11}^2 + S_{21}^2) \right] \quad (4b)$$

The normalized impedance z is calculated as (10) and after it is multiplied with the free space impedance it gets denormalized $Z_L = z * Z_0$ so that the Z_{patch} can be extracted from (5a) and (5b).

$$\Gamma = \frac{Z_{patch} || Z_{in}(d_2) - Z_0}{Z_{patch} || Z_{in}(d_2) + Z_0} \quad (5a)$$

$$Z_L = \frac{1 + \Gamma}{1 - \Gamma} \quad (5b)$$

It is also worth noting that the absorber can be modeled as an equivalent electrical circuit.

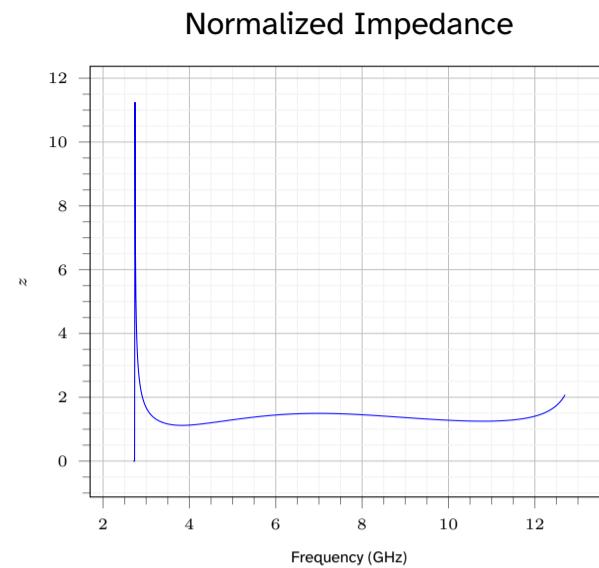
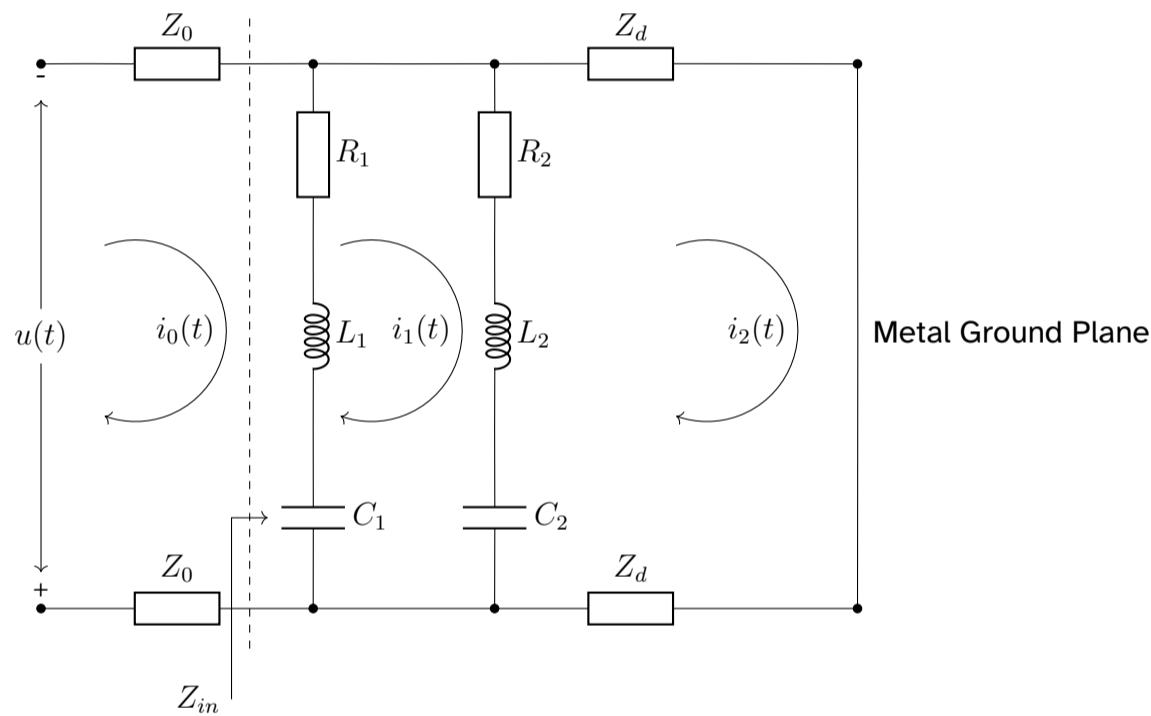


Figure 10: $\Re(z)$



Where the ...

IV Optimization

For this step the IdeM package as well as matlab in order to tweak the parameters that describe dimensions...

V Discussion

Reducing the plasma frequency of metals in MMAs allows them to operate effectively at lower frequencies, expanding their applicability to various frequency ranges. This is achieved by manipulating the density of free electron carriers in the metal.

References

- [1] V. G. Veselago and E. E. Narimanov, "The left hand of brightness: Past, present and future of negative index materials," *Nature Materials*, vol. 5, no. 10, pp. 759–762, Oct. 1, 2006, ISSN: 1476-1122, 1476-4660. doi: 10.1038/nmat1746. [Online]. Available: <https://www.nature.com/articles/nmat1746> (visited on 11/05/2024).
- [2] Y. Zhang, W. Yang, X. Li, and G. Liu, "Design and analysis of a broadband microwave metamaterial absorber," *IEEE Photonics Journal*, vol. 15, no. 3, pp. 1–10, Jun. 2023, ISSN: 1943-0655, 1943-0647. doi: 10.1109/JPHOT.2023.3277449. [Online]. Available: <https://ieeexplore.ieee.org/document/10129034/> (visited on 11/05/2024).