UNIVERSITAT POLITÈCNICA DE VALÈNCIA

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Estudio sobre la mitigación de resonancias en blindajes metálicos para circuitos integrados

Trabajo Fin de Grado

Grado en Ingeniería de Tecnologías y Servicios de Telecomunicación

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I would like to thank my family, teachers, friends and classmates for the delivery of this Final Degree Project.

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Abstract

Inherent cavity resonant modes often lead to significant degradation of shielding effectiveness, responsible for unwanted electromagnetic coupling among different electronic components inside the enclosure. The tendency of an ever-increasing number of electronic components to be integrated into a limited space lead to unwanted coupling that may generate system malfunction.

Cavity resonant modes of the metal shielding enclosure can produce two adverse problems: the mutual coupling among different RF modules and shielding effectiveness reduction of the metal enclosure.

Some research studies have shown that cavity resonant modes can be damped by coating lossy materials onto the inner walls of a shielding enclosure. Therefore, this project is focused on evaluating the use of WE-FAS TC (Würth Elektronik product) to reduce these undesired effects apart from helping with the thermal management of this enclosures.

Keywords: shielding effectiveness, thermal management, EMI, cavity resonant.

Resumen

Los modos resonantes inherentes a la cavidad suelen provocar una degradación significativa de la eficacia del apantallamiento, responsable del acoplamiento electromagnético no deseado entre los distintos componentes electrónicos del interior de la carcasa. La tendencia a integrar un número cada vez mayor de componentes electrónicos en un espacio limitado conduce a acoplamientos no deseados que pueden generar un mal funcionamiento del sistema.

Los modos resonantes de cavidad de la envolvente metálica de blindaje pueden producir dos problemas adversos: el acoplamiento mutuo entre diferentes módulos de RF y la reducción de la eficacia de blindaje de la envolvente metálica.

Algunos estudios de investigación han demostrado que los modos resonantes de cavidad pueden amortiguarse recubriendo las paredes interiores con materiales absorbentes a base de ferrita. Por lo tanto, este proyecto se centra en evaluar el uso de WE-FAS TC (producto de Würth Elektronik) para reducir estos efectos no deseados, además de ayudar con la gestión térmica de estas cavidades.

Palabras clave: efectividad del blindaje, gestión térmica, EMI, cavidades resonantes.

Resum

Els modes ressonants inherents a la cavitat solen provocar una degradació significativa de l'eficàcia de l'apantallament, responsable de l'acoblament electromagnètic no desitjat entre els diferents components electrònics de l'interior de la carcassa. La tendència a integrar un nombre cada vegada major de components electrònics en un espai limitat conduïx a acoblaments no desitjats que poden generar un mal funcionament del sistema.

Els modes ressonants de cavitat de l'envolupant metàl·lica de blindatge poden produir dos problemes adversos: l'acoblament mutu entre diferents mòduls de radiofre i la reducció de l'eficàcia de blindatge de l'envolupant metàl·lica.

Alguns estudis d'investigació han demostrat que els modes ressonants de cavitat poden esmorteir-se recobrint les parets interiors amb materials absorbents a base de ferrita. Per tant, este projecte se centra en avaluar l'ús de WE-FAS TC (producte de Würth Elektronik) per a reduir estos efectes no desitjats, a més d'ajudar amb la gestió tèrmica d'estes cavitats.

Paraules clau: efectivitat del blindatge, gestió tèrmica, EMI, cavitats resonants.

RESUMEN EJECUTIVO

La memoria del TFG del “Resonant cavities: study of their behaviour and mitigation of their effects by means of a ferrite absorber sheet.” debe desarrollar en el texto los siguientes conceptos, debidamente justificados y discutidos, centrados en el ámbito de la electrónica.

CONCEPT (ABET)	CONCEPTO (traducción)	¿Cumple? (S/N)	¿Dónde? (páginas)
1. IDENTIFY:	1. IDENTIFICAR:	S	
1.1. Problem statement and opportunity	1.1. Planteamiento del problema y oportunidad	S	11
1.2. Constraints (standards, codes, needs, requirements & specifications)	1.2. Toma en consideración de los condicionantes (normas técnicas y regulación, necesidades, requisitos y especificaciones)	S	16-27
1.3. Setting of goals	1.3. Establecimiento de objetivos	S	12
2. FORMULATE:	2. FORMULAR:	S	
2.1. Creative solution generation (analysis)	2.1. Generación de soluciones creativas (análisis)	S	28-37
2.2. Evaluation of multiple solutions decisionmaking (synthesis)	2.2. Evaluación de múltiples soluciones y toma de decisiones (síntesis)	S	28-37
3. SOLVE:	3. RESOLVER:	S	
3.1. Fulfilment of goals	3.1. Evaluación del cumplimiento de objetivos	S	53
3.2. Overall impact and significance (contributions and practical recommendations)	3.2. Evaluación del impacto global y alcance (contribuciones y recomendaciones prácticas)	S	53

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DIY	Do It Yourself
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FAS	Ferrite Absorber Sheet
FAS TC	Ferrite Absorber Sheet Thermal Conductive
FSFS	Flexible Sintered Ferrite Sheet
SDG	Sustainable Development Goals
SHC	Shielding Cabinet
SMT	Surface Mount Technology
THT	Through-hole Technology
WE	Würth Elektronik

Part I

Descriptive Memory

Chapter 1

Introduction

1 Context

The technological development over the last decades has been unprecedented, starting in the 2000s with just phones capable of making calls, to the present day, with augmented reality glasses, hyper-connectivity and high speeds devices.

In order to achieve this development, it has been necessary to design the hardware of all operating systems to be smaller and more optimal. Consumers and the technology industry demand higher portability, faster speeds and high quality performance.

With this challenge in mind, and assuming that designs will not only remain as they are, but will become smaller and smaller, the industry faces a major challenge of Electromagnetic Interference (EMI).

Components increasingly close together and working at higher frequencies give rise to new design challenges that did not exist before. Industry is no longer talking about eliminating electromagnetic interference effects, but rather, assuming that such problems will occur, looking for a method to mitigate their effect.

Many designers are opting to include shielding cabinets, a product that will be discussed in this thesis, to isolate components that emit a lot of electromagnetic radiation from the rest of their PCB components. However, this solution may not be 100% effective at certain frequencies, resulting in a resonant cavity effect and therefore not achieving the desired isolation.

In this work, a study of magnetic resonances in different WE-Shielding Cabinet (SHC) will be carried out, both at simulation and practical level. Once the resonances have been located, the WE-Ferrite Absorber Sheet Thermal Conductive (FAS TC) material will be used to mitigate this effect and help the thermal management of the cavity.

For all these reasons the title of this thesis is:

Resonant cavities: study of their behaviour and mitigation of their effects by means of a ferrite absorber sheet.

This final degree project is presented in collaboration with the "Würth Elektronik catedra" at the University of Valencia. A laboratory and office space where more than ten people carry out research work with the company's most cutting-edge products.

The author of this work has been working for nearly a year in this association on research projects with thermal and shielding products.

It is a unique space where not only students and professors work together, but also where Valencian companies can consult and collaborate with WE.

It is the author's intention to continue the professional relationship within the organisation after completion of the degree.

2 Objectives

The main objectives to be achieved during this work are:

- To identify by means of simulations with Ansys software[1] and theoretical calculations the resonant cavities of different types of WE cabinets.
- To identify by testing if the resonances found in the simulations coincide with what happens in reality.
- Simulate and test the application of WE-FAS TC [2] as a mitigator of these resonances. This material is used by WE customers to absorb electromagnetic noise.
- Test the impact of the thermal properties of WE-FAS TC.

A secondary objective is to perform a series of tests that do not only consist of placing as large a piece of WE-FAS TC as possible to dampen the resonance. The aim is to optimise the position and amount of area to be covered by the material in order to achieve the best result.

This will be done by observing in the Ansys simulations the hot spots where the electromagnetic field is at its maximum and placing the material there for the real tests.

It is important to note that within the WE portfolio there are many types of cabinets, not only in shape but also in size, it is not the purpose of this thesis to study all the types of cases that the company has, as the combinations are infinite.

The initial hypothesis is that by combining an accurate simulation with an appropriate location of the absorber, the resonance frequency can be attenuated and therefore the performance of the cabinets can be optimised. Once this has been demonstrated, WE's different customers can make their requests specifying the specific case: type of cabinet, size etc. and carry out the same procedure for their design.

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[1] https://www.ansys.com/

[2] https://www.we-online.com/en/components/products/WE-FAS-TC

3 Würth Elektronik

Würth Elektronik (WE) group of companies, with headquarters in Niedernhall (Hohenlohe), Germany, has about 8,000 employees worldwide and generated global sales of € 1.09 billion in 2021.

With 23 production locations around the world, WE operates internationally with its three company areas in various markets. In the case of this thesis, the study has been carried out at the facilities located at the University of Valencia, Spain.

The entity offers three main types of services. On the one hand, the production of PCBs for all types of applications. Secondly, intelligent power and control systems such as for example power distributors or high voltage solutions. Finally, they also offer electronic and electromechanical components: passive components, optoelectronics, wireless connectivity and sensors.

For the thesis, the products to be used are passive components, namely two: the shielding cabinets and the WE-FAS TC, both within the shielding portfolio.

Moreover, the company's motto is: **more than you expect**. A motto that has also served as inspiration for the improvement of the utility of these two products.

Figure 1.1 shows WE logo.

Figure 1.1: Würth Elektronik official logo. Source: WE website

4 Motivation

Technology is advancing by leaps and bounds, and even the society is not able to keep up with all the innovations that occur year after year.

However, persons have the ability to anticipate challenges even when everything is moving so fast. In this new generation of hardware design, there is a world of possibilities, combinations and approaches to realise the technology of the future.

But each and every one of them will share the intention to perform better and be more compact, so they will all face the challenge of condensing many components that require high performance, affected by EMIs.

This thesis is an opportunity to provide a universal solution to certain challenges the industry will face, regardless of the specific domain and with the versatility of not being limited to a single operating frequency range.

The main motivation is to provide a working methodology to study the resonances of a design and to demonstrate that there are viable solutions to mitigate these effects.

The future of PCB design will not depend on the inherent challenges of component compaction.

The limit, with a little luck and a lot of research, will be set by the designers.

5 Sustainable Development Goals(SDG) related to the project

The project is mainly related to one sustainable development goal:

- Industry, innovation and infrastructure (number 9).
- Ensure sustainable consumption and protection patterns (number 12).

The SDG number 9 is really in line with the project, since the aim is precisely to empower innovation at the hardware design level by facilitating the challenges that are already beginning to appear and that will be even more pronounced in the future.

The aim of simulating the distribution of the magnetic field inside the cabinet in order to place the right amount of material is precisely the same as the objective number 12. A responsible production where no material is wasted, but where thanks to the tools already developed, the amount of material can be optimised without waste.

Chapter 2

Theoretical framework

1 Cavity resonances

1.1 Definition

A shielding cabinet is a cavity, of variable size, formed by a highly conductive material (usually a metal) that seeks to shield a component and/or element from electromagnetic radiation. With this purpose in mind, the cavities that concern this work are those of a very small size, barely exceeding thirty millimetres in width and length and five millimetres in height, which are located in PCBs as protection for critical components.

Within a closed cavity, the field equations reveal that it is possible to have standing waves modes existing within the cavity. This can occur within an empty, enclosed space as long as the cavity sizes are greater than or equal to half the size of the free-space wavelength.

Resonance modes can be several, however the one studied here is the TE01 mode because it is the mode that appears at the lowest frequency. So there may be other modes or they may be predominant, they are not an object of interest because they occur at very high frequencies at which the technology currently does not work.

Figure 2.1 shows an example of a resonant cavity within a cabinet:

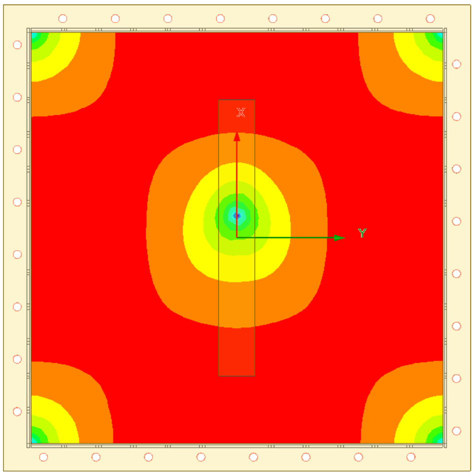

Figure 2.1: Cavity resonance. Source: Ansys original design

To clarify, the image shows the distribution of the magnetic field in the cabinet, showing in the borders the concentration of the field and therefore the main focus to mitigate. This occurs at a certain frequency, depending on the size of the cabinet, the image shown is just an example to visually understand what is involved in a resonance within a cabinet.

The red colour indicates areas where the magnetic field has a higher value and therefore generates more interference. Resonances inside a cavity are an element to be taken into account, since what is happening is that inside the cavity the signal "bounces" creating a very strong field that can cause the component to work in worse conditions.

For a rectangular cavity, with dimensions a, b, c and a>b>c, and which is completely filled with a homogeneous material, the equation for the resonant frequency is:

$$f_{mnp} = \frac{1}{2 \cdot \sqrt{\epsilon \cdot \mu}} \cdot \sqrt{(\frac{m}{a})^2 + (\frac{n}{b})^2 + (\frac{p}{c})^2} \tag{2.1}$$

In this equation ε is the material permittivity and μ is the material permeability.

It should be noted that although all cavities at a given frequency exhibit resonances, if there is a device inside the cavity that operates below this cut-off frequency, the device should not be affected by resonances.

In this thesis the first resonance mode is calculated which involves setting the following parameters:

- m= 1
- n= 1
- p=0

This is the first frequency in which resonances appear and it is also the most predominant, so it is the parameter of interest to attenuate.

Knowing the frequency is key not only to identify when designing if there will be resonance challenges, but also, when choosing an absorbing material, the frequency at which it must absorb will be differential for choosing the thickness of the material, as will be seen in Section 1.5.

1.2 State of art

Resonant cavities are relatively new, not because their possible existence was unknown in the early 2000s, but because they did not pose a real challenge to designers.

Recently, however, the explosion of 5G and new technologies has allowed us to start exploring much higher working frequency ranges, making these resonances something to be studied and taken into account when implementing a design.

A May 2004 study by Paul Dixon ([2]) already talks about how to attenuate the resonant cavity effect by using ferrite absorber materials. In this study he shows how depending on the absorber material, its thickness and size can vary the effect on the resonance.

It also highlights the importance of the placement of the material inside the cabinet, but does not show numerical results of how much the resonance was attenuated in the different conditions, nor simulations or set up.

In addition to this study focusing on cabinets plus absorber material, numerous studies have been carried out on the properties of the absorber material at different frequencies. For example in the case of Kenneth Wyatt who in July 2019 ([6]) conducted a study to characterise the insertion loss of various absorber materials including some from WE. This study is more analytical than the first one and shows set up, graphs and results.

The aim of this project is to provide a combination of the more analytical part with simulations, material characterisation and real-life testing, in combination with appropriate documentation on how to locate resonances in cabinets for designers and real, measurable solutions to mitigate these resonances.

1.3 Shielding at high frequencies

When talking about shielding, the first term that often comes to mind is the Faraday cage. At low frequency, the electrons can move sufficiently far between the peak and valley of the wave to allow a redistribution of charge: an electric field appears which opposes the external one, achieving a zero electric field in the region surrounded by the screen.

However, in this work, the ranges that are of interested are high frequency ranges, so the electrons do not have as much freedom of movement and therefore the Faraday cage effect is much smaller.

In these frequency ranges two main effects have to be taken into account: reflection and absorption, and secondly the absorption inside the cavity walls has to be taken into account.

Figure 2.2 shows an scheme of these properties:

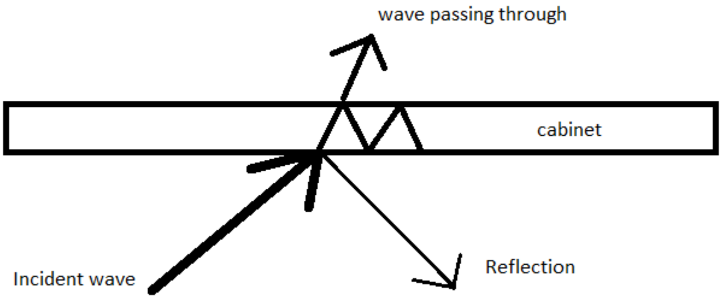

Figure 2.2: Reflection and absorption in a shielding cabinet. Source: Original content

The interaction between the shielding and the electromagnetic wave depends on the thickness, conductivity and magnetic permeability of the cabinet, as well as the frequency and characteristics of the wave. As seen in the image, not only can there be a reflection of the wave within the cabinet, but there is also a part of the wave that passes through it and ultimately within the walls of the cabinet itself, the signal can bounce and become attenuated.

It is not the purpose of this work to study how much wave is reflected, how much is attenuated on the walls of the cabinet and how much is emitted outside, but it is key to understand what is happening to then comprehend what happens when there is a frequency resonance inside a cabinet.

The objective of a cabinet is for the element inside (in this case a microstrip) to be protected from outside interference or, on the contrary, to protect the rest of the components from a component that can cause interference.

In the case of this work, the microstrip is used to emulate that there is a component operating at certain frequencies (of the order of GHz) and in this case the antenna has an emission peak around 5GHz.

If, due to the phenomenon of reflection inside the cabinet, what ends up happening is that the component itself suffers interference, the cabinet would not be fulfilling its function well, because although it is true that the surrounding components may not be affected, the component inside the cabinet itself will stop working correctly due to internal self-interference.

Ideally, the majority of the field would be attenuated in the thickness of the cabinet itself, without excessive reflection or passage of the wave to the outside. But that is not always possible as will be seen in this work and therefore sometimes it is necessary to use absorbent materials as seen in Figure 2.3.

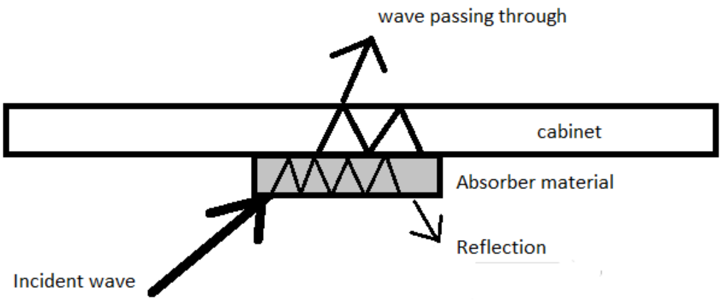

Figure 2.3: Shielding with absorber material. Source: Original content

What is achieved by inserting an absorbing material is to increase the percentage of the absorbed wave between the thickness of the material and the cabinet, reducing the percentage of the reflected wave. This reduces internal interference and therefore allows the material to continue operating in a greater frequency range.

As for the wave that leaves the space, it will also be of lower intensity (therefore it benefits the components that are outside). The signal "leaks" from inside the cabinet to the outside are not only due to what passes through the material and its wall, it also affects the cabinet having slots, poor welding that leaves gaps between the cabinet and the pcb, etc. but this is not the object of study for this work.

1.4 Shielding cabinets

WE-Shieding Cabinets(SHC) is one of the flagship products in the company's portfolio, as it is a solution that attenuates and even eliminates electromagnetic interference from critical system components and can be incorporated from an early design stage at a drastically reduced cost.

In its standard format, companies have the opportunity to incorporate a cabinet footprint on their PCB. They are usually placed in components that have high clock frequencies or that are going to radiate electromagnetic fields towards other components causing noise. But the opposite can also happen, they can be placed on components that do not radiate, but may be subject to radiation. It is up to the designer whether to neutralise the source of the noise emission or to shield the receiver from it.

A picture of the product can be found in Figure 2.4:

Figure 2.4: WE-SHC portfolio. Source: WE website

The product works like a electromagnetic shield so that everything inside or outside of it is shielded from electromagnetic radiation. In addition, it is key that the footprint of the cabinet is grounded, to achieve that the cabinet does not work as an antenna.

Within the WE portfolio, Figure 2.4 shows that there is not just one type of cabinet, but multiple options. If they are differentiated by their mode of manufacture they are:

- Shielding cabinets standard: based on the cutting and punching manufacturing method and therefore there are small holes in the corners of the cabinet.
- Shielding cabinets seamless: based on a deep drawing method of manufacture and this ensures that the material is continuous and compact, with no openings.

Figure 2.5 shows the two products in order to see the differences:

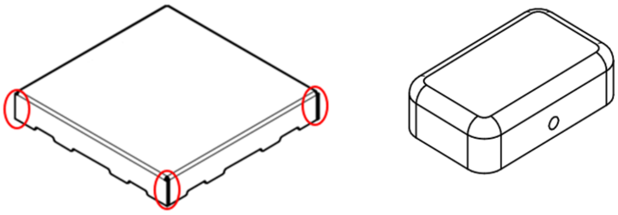

Figure 2.5: Standard vs seamless cabinet. Source: WE internal departments

As can be seen in Figure 2.5, standard cabinets have small millimetre-sized openings, but at very high frequencies these can affect shielding effectiveness of the cabinet, which is why the seamless version was developed to achieve an even more shielding effect in a higher frequency range.

Apart from the way they are manufactured, cabinets can also be differentiated by their composition:

- With holes: Small openings in the cabinet lid to prevent overheating.
- Without holes: No thermal management encourage.

Figure 2.6 shows a cabinet with holes:

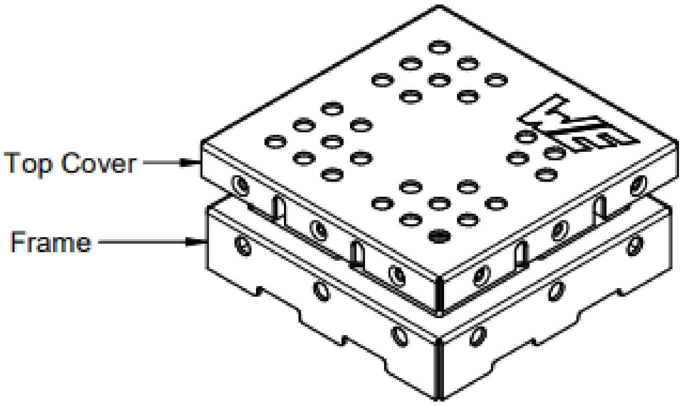

Figure 2.6: Cabinet with holes. Source: WE portfolio

These types of cabinets are highly complex to simulate to find resonances and if an absorbent material were placed on the lid it would cover many of the holes, removing their thermal management functionality. This is why it does not make sense to carry out a study of them for the present work.

Finally, there are two types of anchoring to the PCB:

- Surface Mount Technology (SMT)
- Through-hole Technology (THT)

Figure 2.7 shows the difference in anchorage on the PCB:

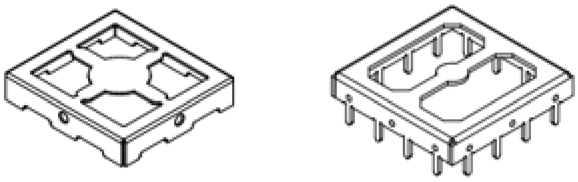

Figure 2.7: SMT vs THT. Source: WE internal departments

It is important to note that the left (SMT) mounting leaves more space between the PCB and the cabinet itself, however, if the soldering is done correctly, it should not be a disadvantage for proper sealing. For this thesis, the PCBs used in the SMT system.

Moreover, cabinets can come in one or two pieces, as shown in Figure 2.8:

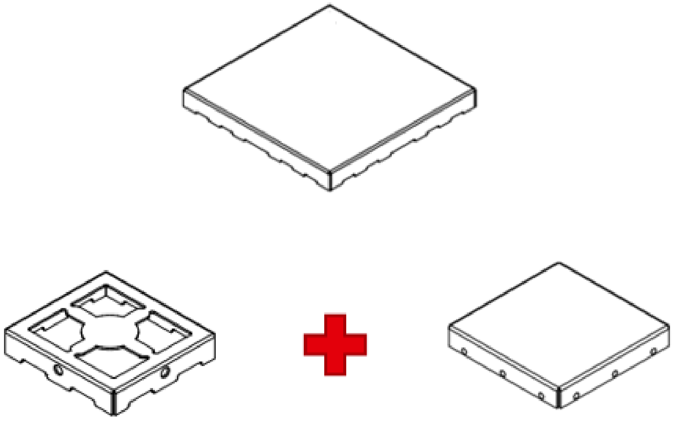

Figure 2.8: One vs two pieces. Source: Original source

The reason for making a two-piece option is because in some cases you want to solder the base of the cabinet but before the final delivery of the product, it is necessary to see the component under the cabinet during testing, to see some data, measure temperature or any other reason.

The two-piece option is not so much designed to remove and replace the lid, but rather to solder the base of the WE-SHC and to be able to continue testing until the cavity is completely closed.

Finally, WE has released a cabinet option that can be assembled by hand, the Do It Yourself (DIY) cabinet. This type of cabinet consists of a nickel plate only 0.2 millimetre thick that can be cut and assembled in different sizes. The aim is that designers can try it out before ordering a cabinet (custom or standard) for their design.

Figure 2.9 shows the sheet used to make these cabinets:

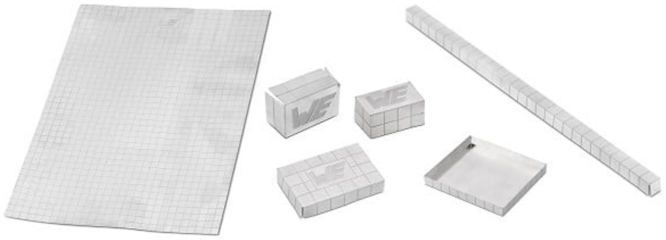

Figure 2.9: DIY. Source: WE internal departments

In this project, three types of cabinets will be studied:

- Two-piece square (31x31x5mm) shielding cabinet.
- Shielding cabinet seamless.
- DIY cabinet (30x30x5mm).

1.5 WE-FAS

The main purpose of a FAS is electromagnetic wave absorption and noise suppression. From the point of view of electromagnetic compatibility, these materials can be strategically placed at the sources where these interferences occur to absorb the noise.

Figure 2.10 shows an example of the placement of this material:

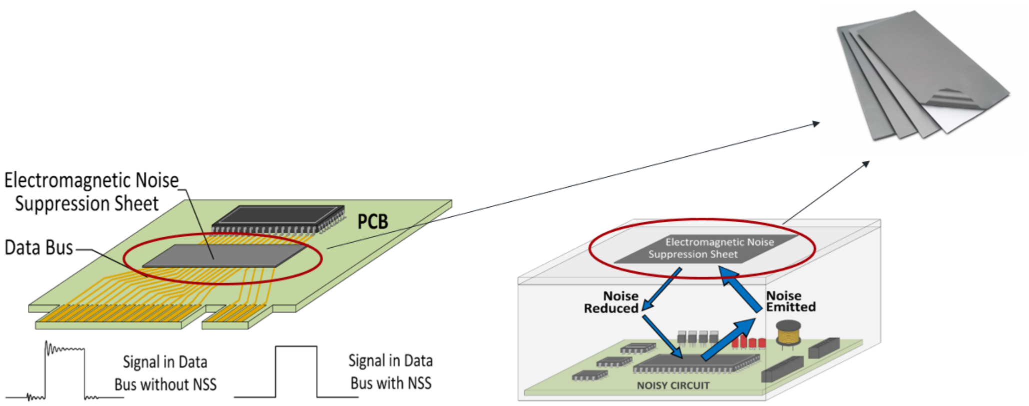

Figure 2.10: FAS Application. Source: WE internal departments

Two examples of application are shown in the picture. The first one is about data paths that are very close to each other and can generate cross talk, by placing the material just above them, it avoids the exchange of noise between them.

In the second case, one could imagine that the components are under a cabinet and one of them emits noise, to prevent this noise from bouncing off the walls of a cabinet a FAS is placed. This example is the closest to what concerns this thesis.

These materials have different thicknesses because depending on the wavelength (i.e. frequency) the material has absorption peaks at one thickness or another. In low frequency applications (below 1 GHz) thicker thicknesses are usually ideal, but as the frequency increases, the material required is usually thinner.

Another material option that WE has is WE-Flexible Sintered Ferrite Sheet (FSFS) which also has attenuation and noise suppression properties, however for this project they have not been chosen as they are more reflection oriented than absorption oriented.

2 Cabinets thermal management

2.1 Thermal context

The components on a PCB spend a lot of time working, whether inside a mobile phone, television, radio or any current technology. This long life and intense use of electronic devices means that these components can overheat.

The way an element is cooled can be by convection (using air), conduction (through different materials) or radiation (which occurs naturally in all bodies).

Between convection and conduction, for the specific application of this thesis it has been chosen conduction method. This is because the component will be encapsulated inside a cabinet of just a couple of centimetres, leaving the option of including a fan inside impossible. Even if it were possible to do so, the air would be moving inside the cavity itself, which would not result in a decrease in temperature.

However, by means of conduction, integrating a low-resistance material, heat flow from the component to the metal cavity can be encouraged. The metal housing of the cabinet is optimal to guide heat to flow outwards.

This property of "directing" heat is known as thermal conductivity. Thermal conductivity refers to a material's intrinsic ability to transfer or conduct heat(**[5]**).

Figure 2.11 shows visually how this variable influences the heat flow:

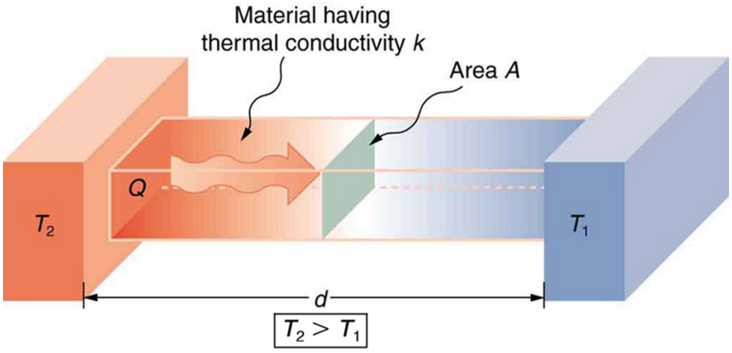

Figure 2.11: Thermal conductivity. Source: Khan Academy

The thermal conductivity is a key parameter to obtain the heat flux value of the component to the outside of the cabinet, which is given by Fourier´s equation:

$$Q = \frac{k * A * (T2 - T1)}{d} \tag{2.2}$$

The heat flow between the hotter component (the one inside the cabinet) and the outside of the cabinet is highly conditioned by the temperature difference between the two elements, the thermal conductivity of the material placed between them and their distance (material thickness).

It is important to optimise the contact area of the components with the material so that the heat flow is more optimal, this will be a priority when deciding which component to place inside the cabinet for the test.

2.2 WE-FAS TC

Within the company's portfolio it was decided that the FAS could have even more potential, so it was decided to develop the WE- Ferrite Absorber Sheet Thermal Conductive (FAS TC).

This product combines the properties of a FAS with the addition of a thermal interface. This interface replaces the convective thermal resistance from the component to the lid though air with a conductive resistance, which is at least one order of magnitude smaller.

Figure 2.12 shows an image of the FAS TC:

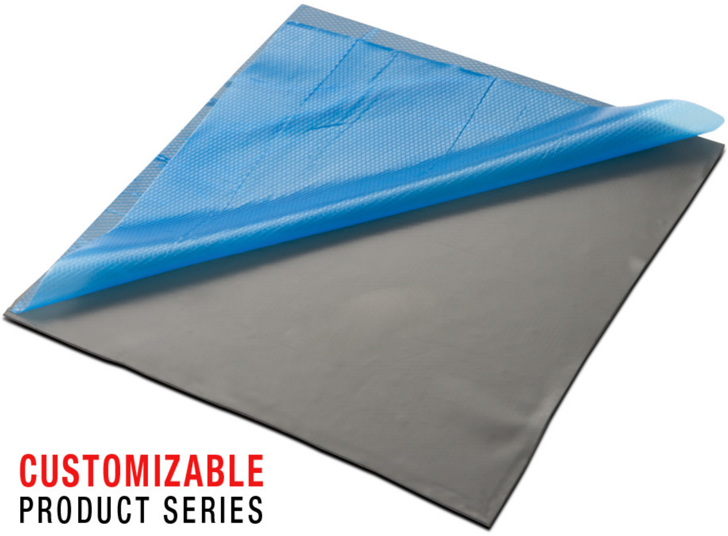

Figure 2.12: WE-FAS TC. Source: WE website

To understand an example application, Figure 2.13 shows a heat source that could be a component of any PCB and a red material (emulating WE-FAS TC) that favours the heat flow to a heatsink.

Figure 2.13 shows an image of FAS TC Application:

Figure 2.13: WE-FAS TC Application. Source: WE internal departments

For this work, it has been decided that this product was the optimal one to attenuate the resonant cavities, because by fulfilling the same properties as the FAS, better thermal management could be achieved.

Chapter 3

Methodology

The proposed method is based on three fundamental steps, first of all a theoretical obtaining of where the resonance frequencies should appear. Followed by simulations that will be validated to see if the resonance frequency appears where it has been calculated theoretically.

Finally, a validation in laboratory will be done to check if what is expected in the theoretical part really happens.

1 Theoretical data

1.1 Shielding

To obtain the theoretical data, formula shown below has been used:

$$f_{mnp} = \frac{1}{2 \cdot \sqrt{\epsilon \cdot \mu}} \cdot \sqrt{(\frac{m}{a})^2 + (\frac{n}{b})^2 + (\frac{p}{c})^2} \tag{3.1}$$

A key parameter for this formula is the relative permittivity of the box. If it were a closed box, the relative permittivity could be considered to be that of air ($\epsilon = 1$).

However, it was found within WE that working with this permittivity, the theoretical results did not resemble those tested in reality. This is because anchoring the cabinet to the mass plane of the PCB conditions its relative permittivity. It is not only the air that has to be taken into account, but also the FR4 (the material the PCB is made of).

To calculate the actual relative permittivity that the cavity is experiencing, it must be taken into account that the junction of the cabinet with the PCB is equivalent to the junction of two capacitors in series as shown in Figure 3.1:

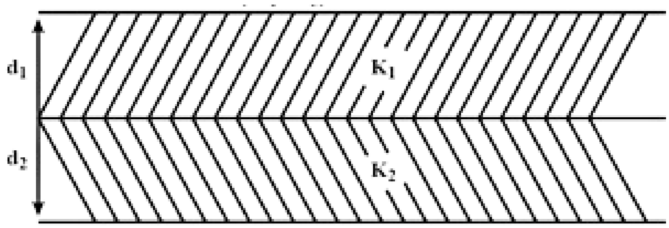

Figure 3.1: Two capacitors in serie. Source: Original source

The formula for the capacity of a capacitor is:

$$C = \frac{K * \epsilon * A}{d} \tag{3.2}$$

So the formula of two capacitors in series would result in:

$$1/C_{eq} = \frac{1}{C1} + \frac{1}{C2} \tag{3.3}$$

Therefore the total capacity (Ceq) has to be calculated as the series conjunction of the cabinet (C1) with the capacity of the PCB (C2). And therefore in Figure 3.1, K1 emulates the cabinet and K2 represents the FR4 of the PCB.

This formula evolves so that the equivalent capacity is equal to:

$$C_{eq} = \frac{K * \epsilon * A}{d1 + d2} = \frac{(K1 + K2) * \epsilon * A}{d1 + d2} \tag{3.4}$$

So it can be solved to obtain the equivalent relative permittivity with the formula:

$$K = \frac{K1 * K2 * (d1 + d2)}{K1 * d2 + K2 * d1} \tag{3.5}$$

This value will be used to obtain the relative permitiviy between cabinet and PCB and finally obtain the real epsilon which will be used for formula 3.1.

The values of each parameter are :

- K1=1 as it is the permittivity of air.
- K2=4.8 as it is the permittivity of the FR4 of the PCB.
- d1=5 (cabinet height)-0.2 (cabinet cover thickness)=4.8 mm
- d2= 1.48 mm (thickness of the PCB)

So the relative permittivity obtain is:

$$K = \frac{1 * 4.8 * (4.8 + 1.48)}{1 * 1.48 + 4.8 * 4.8} = 1.23 \tag{3.6}$$

Knowing this value, size of the cabinet is given by the cabinet manufacturer and has been verified by the author of the thesis by measuring it. Of all the different frequencies at which resonances can occur, this work is designed for the first mode.

Using equation 3.1 and the data calculated, the results obtained are summarised in Table 1.3.1:

Cabinet	Size (mm)	Resonance frequency (GHz)
Standard	31x31x5	6.170
DIY	30x30x5	6.376
Seamless	28x25x5	7.253

Table 1.3.1: Theoretical frequencies summary. Source: Original content.

It is important to note that the seamless is not a square cavity, but has rounded edges, so the data used is an estimate approximating the equivalent of a square shielding cabinet.

2 Simulations

2.1 Ansys Software for shielding simulations

The Ansys simulations were carried out in three steps:

- Simulation of the three cabinets over a wide frequency range (1-10GHz).
- Simulation of the three cabinets in the frequency range where the resonant cavity appeared.
- Simulation of the magnetic field distribution on the top of the cabinets.

The reason for starting a simulation with more frequencies was to check that the resonances did indeed appear in the expected frequency range, as well as to study visually whether unexpected effects appeared at other points.

Refining the simulation was necessary because resonances occur in a very narrow frequency range, and to see the depth of the resonance, many iterations have to be performed in a narrow bandwidth.

Ultimately, this work is not just about finding the resonance and attenuating it by putting a lot of material on the top of the cabinet to absorb it, but also about optimising the amount of material by placing it at the strategic points where it accumulates the most field.

The parameters set for the simulations were common and were as shown in Table 1.3.1:

Parameters	**Values**
Type of simulation	Discrete
Number of points	401
Field plotted	H field
S parameter	0.02
Max. iterations	20

Table 1.3.1: Simulation settings. Source: Original content.

Looking further into the reasons for each choice, the simulation part could be discrete (most accurate but slowest), fast (least accurate but fastest), interpolated (midway between the two). The most accurate but more time-consuming choice was made, as there were only three cases and a very specific range of frequencies had to be studied.

The number of points was given by default, it could be putted more or less, but it turned out to be more than adequate for the ranges that were being studied.

The S parameter is a parameter that indicated the maximum error or divergence between points of the simulation, it is the parameter recommended by Ansys as it keeps balance between precision and simulation time.

Finally the maximum number of interactions is the number of jumps that the simulation makes to achieve convergence (S parameter), normally with 3 or 4 iterations the model achieved the resolution but it was decided to leave margin.

As a common basis for all simulations, the PCB was constructed with the microstrip and the cabinet footprint. Plan view of the PCB can be seen in Figure 3.2:

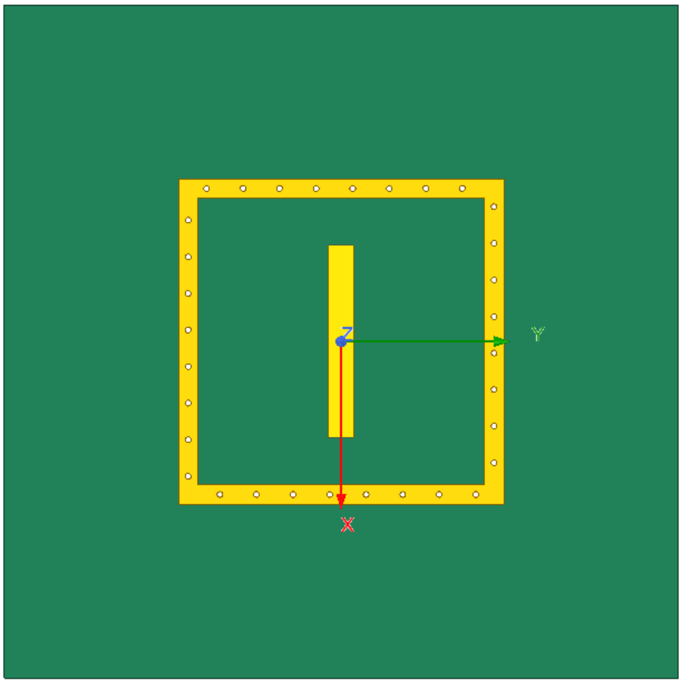

Figure 3.2: PCB in ansys. Source: Original Source

The characteristics of the PCB are shown in Table 1.3.2:

Parameters	**Values**
PCB size	70x70x1.515mm
PCB material	FR4
Footprint material	Copper
Microstrip antenna size	20x2.6mm
Microstrip antenna simulation	Lumped ports

Table 1.3.2: PCB settings. Source: Original content.

All thicknesses, sizes and materials have been chosen to faithfully represent the reality being simulated. Putting two lumped ports at the beginning and end respectively of the microstripline is the most reliable way to represent the microstrip, as you can specify the impedance of the element (50ohm in this case) and it is focused on representing single mode TEM which is the one to be studied.

For a better visualization of the PCB, an isometric perspective with the lumped ports highlights is shown in Figure 3.3:

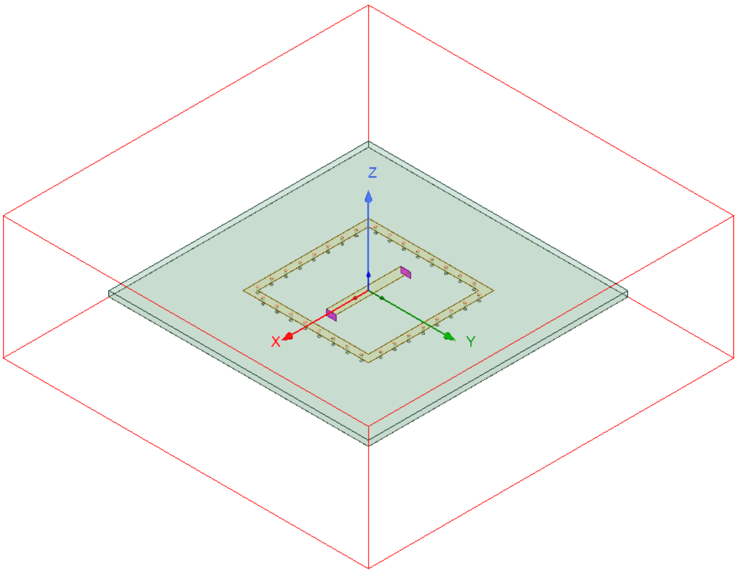

Figure 3.3: PCB isometric view. Source: Original Source

As an example, Figure 3.4 shows the inclusion of a cabinet on top of the PCB:

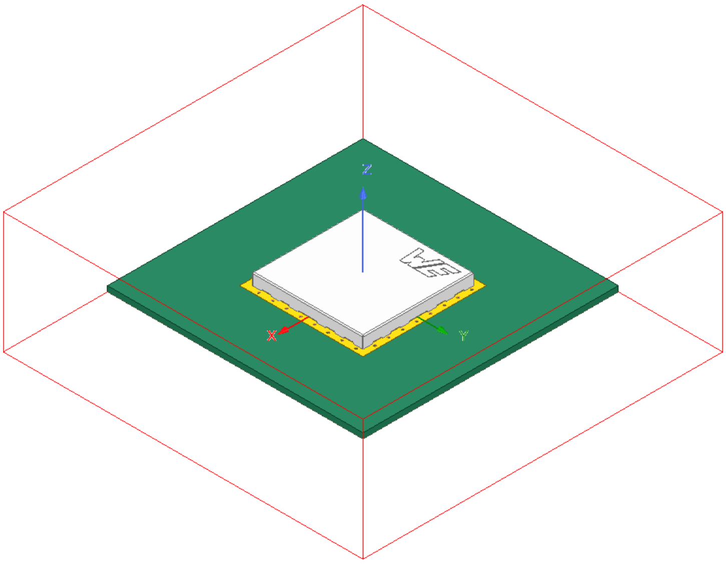

Figure 3.4: Cabinet in ansys. Source: Original Source

The material chosen for the cabinet was nickel, which is the original material. For the simulation the cabinet and footprint must be set up with perfect electrical conditions.

In Figure 3.5 it can be seen the electrical conditions applied in three specific parts:

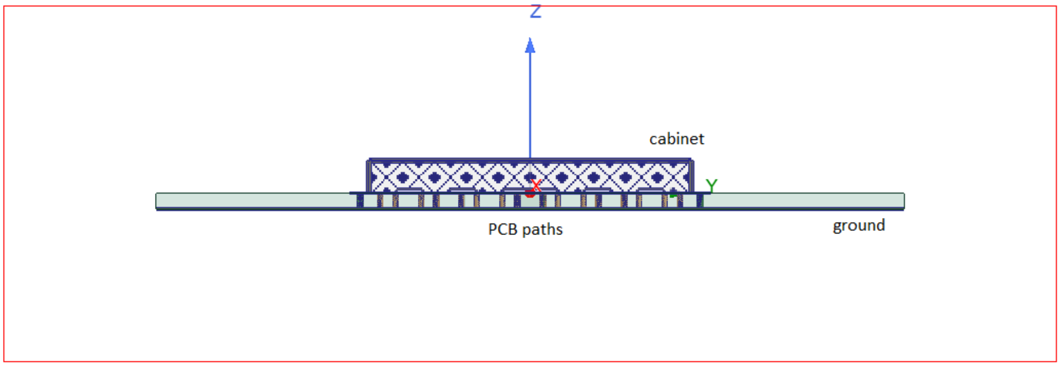

Figure 3.5: Perfect electrical boundaries. Source: Ansys original source

Simulations incorporating the absorbing material cannot be carried out as there is no measuring equipment available within WE that works at high frequencies to parameterise it, so the simulation part will focus only on finding the resonances.

On the other hand, it is not the aim of this thesis to carry out thermal simulations, but there will be an experimental part with the aim of studying the behaviour of the FAS TC outside the scope of the simulation.

2.2 Simscale for thermal simulations

The aim of this work was not to go into the development of a complex simulation at the thermal level and at the beginning it was even considered simply to carry out some tests without simulation.

However, Simscale [1] is an online simulation programme that is intuitive and allows a higher level of precision than a 2D simulation, for example with Excel.

For this reason, and with the aim of a more complete training at a personal level, it was decided to carry out a thermal simulation.

In Figure 3.6 it can be seen the thermal simulation setup:

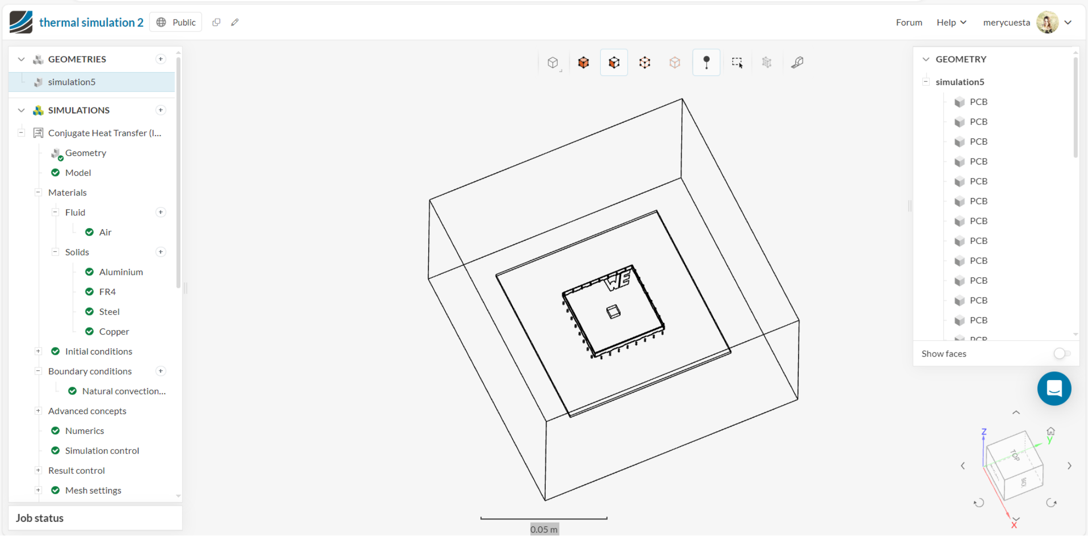

Figure 3.6: Thermal simulation. Source: SimScale

The following materials have been included in this simulation:

- FR4 for the entire PCB
- Metal for the resistor
- Copper for the vias
- Aluminium for the cabinet

A 10 x 10 x 2 mm volume of steel has been used in the simulation to simulate a resistor and set to a temperature of 80 degrees.

In addition, a boundary condition that the PCB is affected by natural convection with an ambient temperature of 24 degrees has been included as this is the temperature that was measured most of the time inside the laboratory where the tests were carried out.

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[1] https://www.simscale.com/

In Figure 3.7 it can be seen the temperature gradient of the simulation:

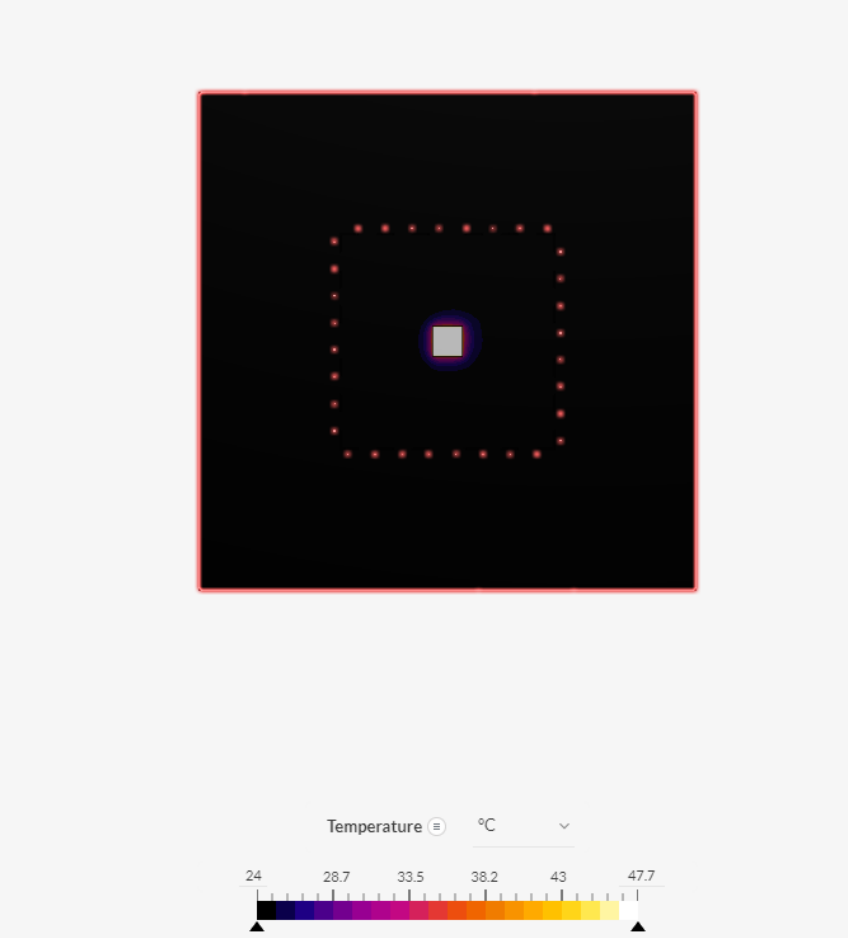

Figure 3.7: Thermal simulation temperatures. Source: Simscale

The majority of the PCB is kept at the original temperature, while it is the resistor that is almost 50 degrees, accumulating heat at a specific point.

In this simulation something was really missing and that was to include a material touching the resistor and the lid of the cabinet to see if the temperature gradient was noticeable. So a second simulation was carried out including a square in the middle, which was assigned as a silicon material and keeping the rest of the conditions exactly the same as in the first simulation.

Figure 3.8 shows the result:

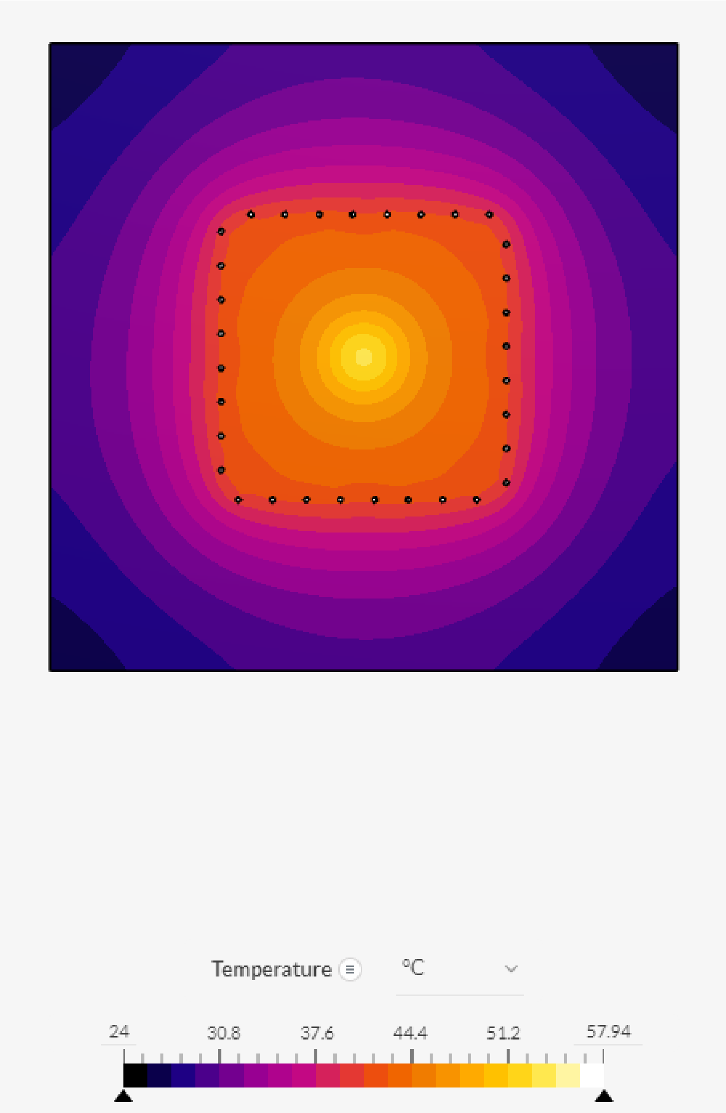

Figure 3.8: Thermal simulation temperatures with silicon material. Source: SimScale

As can be seen the results change drastically, the PCB is no longer all at the same temperature while the resistor accumulates a heat source, but there is a gradient.It is true that the temperature of the subtract (the PCB) is not high, since it is assigned FR4 material, without taking into account the copper part.

Heat flows form the resistor to the lid, increasing its temperature, and evacuating this heat to the ambient via convection, a second benefit of the WE material in this kind of applications. The lid is acting as an extended surface evacuating this heat thanks to have a connection between the heat source (the resistor) and the cabinet through the WE-FAS TC material.

For future simulations, it would be differential to use the exact thermal conductivity of the material instead of the one from silicon but WE didn´t have the data, so in the simulation it was decided to work with the thermal conductivity of the silicon. Even so, the simulation seems to show a positive outlook that the placement of the material also has a thermal advantage.

3 Laboratory setups

3.1 Shielding setup

In order to carry out the resonance measurements, it was necessary to use a network analyser model E5071B **([1])**.

Apart from this tool, the PCB with the microstrip and the footprint for the cabinets is also needed. This PCB will be connected to the network analyser by means of two 50 ohms impedance cables (same impedance as the microstrip). Figure 3.9 shows a picture of these elements separately.

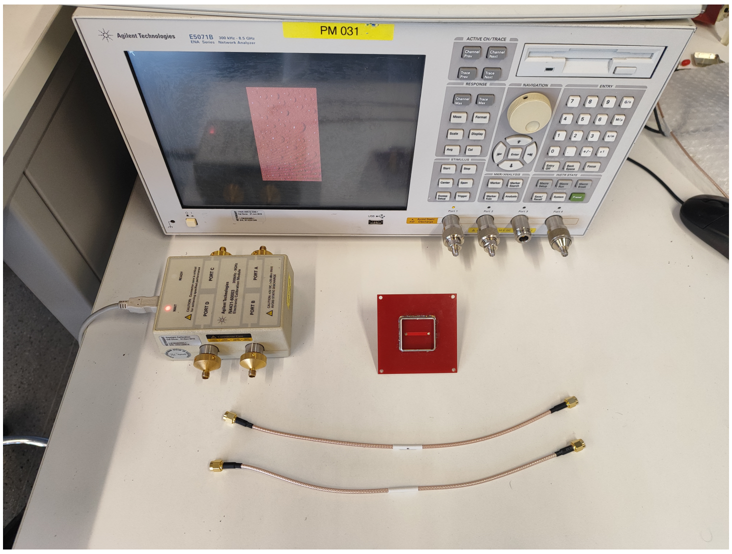

Figure 3.9: Shielding setup. Source: Original Source

In this image the cable calibrator is included, as they must be calibrated before use for the test to work correctly.

In addition to this,the type of cabinet fitted is key to the setup as three different types have been simulated, with different expected results. In Figure 3.10 you can see the three types of cabinets assembled on their respective PCBs:

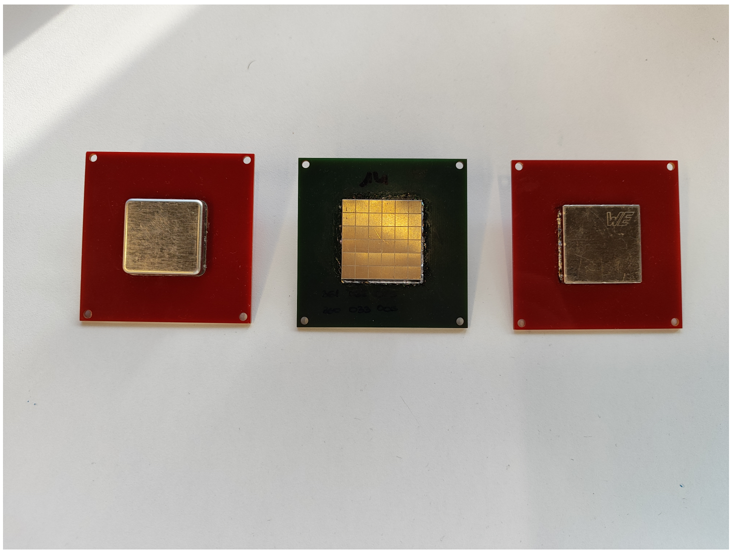

Figure 3.10: Cabinets on PCB. Source: Original Source

Inside these cabinets is where the absorbing material will be placed to study the attenuation of the resonances, as an example of how the material would look like inside is attached in Figure 3.11:

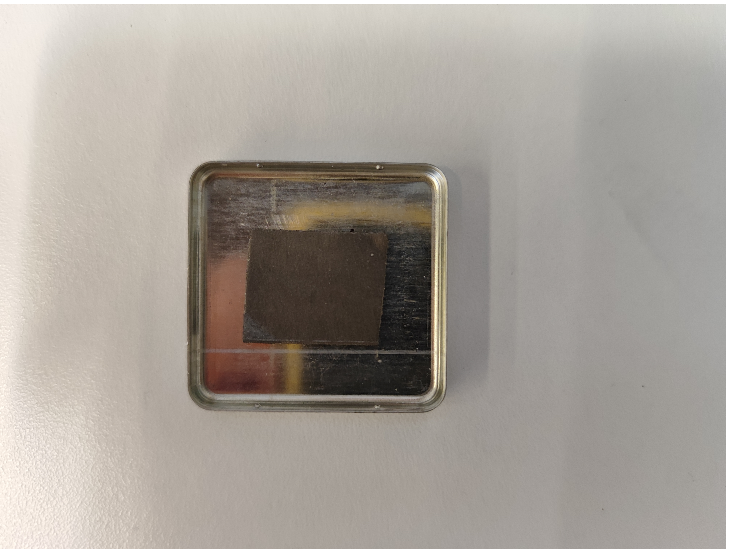

Figure 3.11: FAS TC in the cabinet. Source: Original Source

As the cabinets are in two pieces, the cabinet lid can be put on and taken off to place more material, to remove it or make the necessary variations that need to be made.

3.2 Thermal management setup

For the thermal part the equipment needed was different, no spectrum analyser or cable calibration was required.

This setup consisted of the same PCB used for the cabinets where an 50ohm resistor was incorporated, this was connected to a power supply to allow it to heat up and dissipate power.

Figure 3.12 shows a picture of the setup:

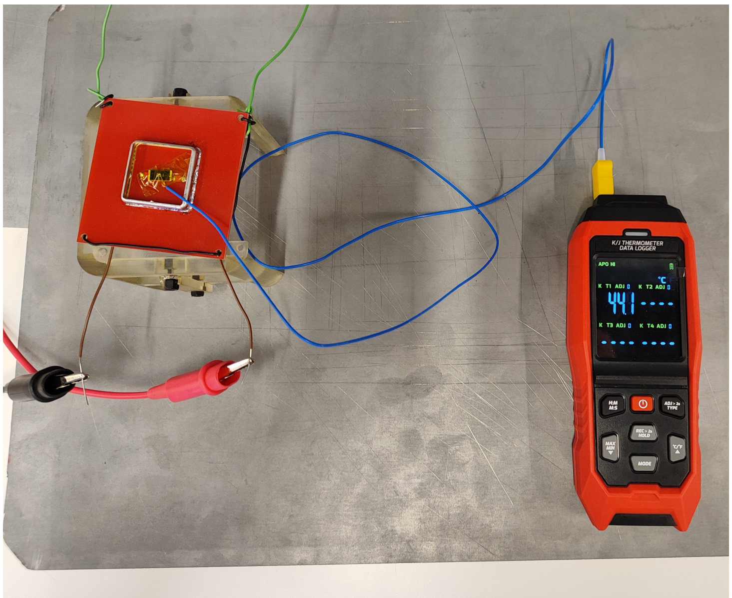

Figure 3.12: Thermal setup. Source: Original Source

To carry out this measurement, the first thing that was done was to sand the PCB in the middle of the microstrip, so that there was no continuity in it and therefore it did not act as an antenna, since what it wanted to be studied in isolation was the heating of the resistor.

The two connectors on the PCB are now used to connect to a power supply that delivers power to the component causing it to heat up.

As seen in Figure 3.12 the temperature of the component is monitored with a thermistor to track the temperature increase over a range of time.

The time it takes for the heating element to heat up from room temperature to 80 degrees will be measured. The datasheet of the resistor ([2]) has been reviewed and although it can withstand temperatures of more than 100 degrees, a good safety margin has been left.

Once the time it takes to reach this temperature has been monitored, it will be measured how much the cabinet temperature rises during the same time and then with WE-FAS TC material between the resistor and the top of the cabinet.

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[2] https://www.mouser.es/datasheet/2/447/PYu$_{A}C_{5}1_{R}oHS_{L}1 1 - 3418659.pdf$

Chapter 4

Development of the project

1 Simulations results

Simulations have been carried out for the three cases studied and in Figures 4.1, 4.2 and 4.3 are shown the plots where the resonance frequency occurrence is located:

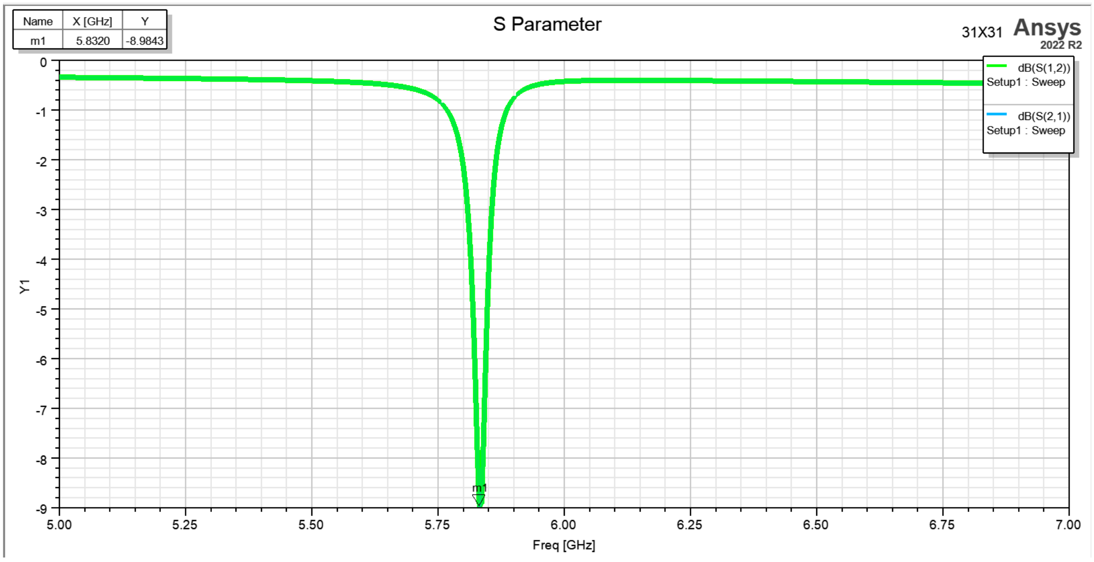

Figure 4.1: 31x31 cabinet result (peak of resonance=5.832GHz). Source: Original Source

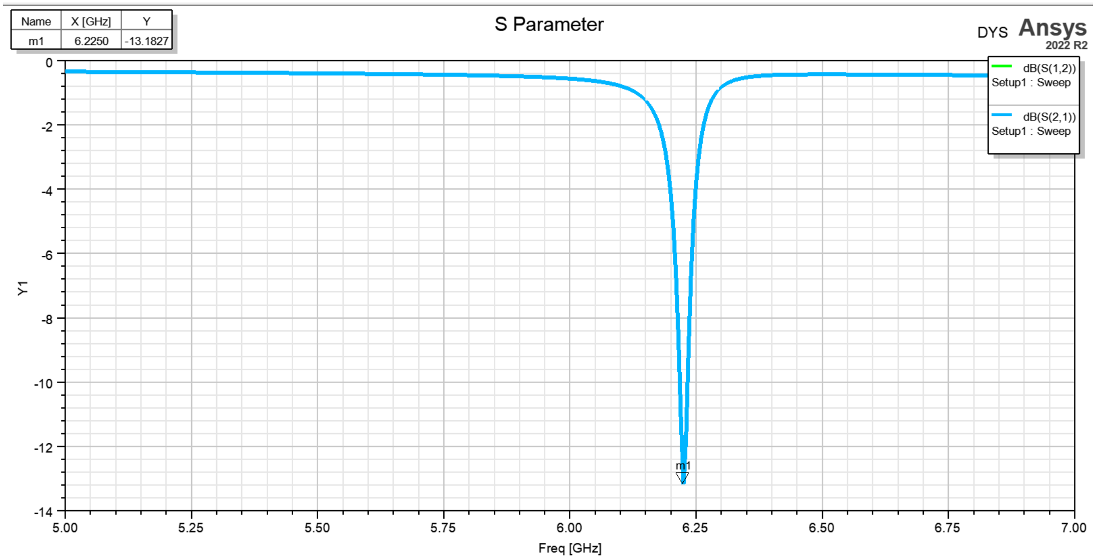

Figure 4.2: DIY cabinet result (peak of resonance=6.225GHz). Source: Original Source

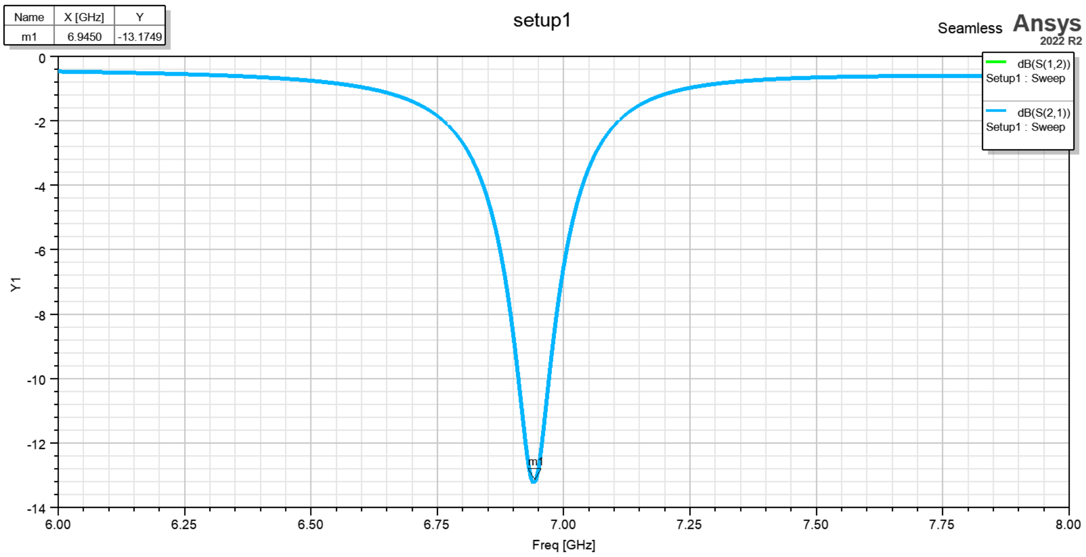

Figure 4.3: Seamless cabinet result (peak of resonance=6.945GHz). Source: Original Source

For a better analysis and comparison, Table 1.4.1 shows the calculated theoretical frequencies and the frequencies obtained in the simulation:

Cabinet	Simulation resonance (GHz)	Theoretical resonance (GHz)	Relative error (%)
Standard	5.832	6.170	5.68
DIY	6.225	6.376	2.36
Seamless	6.945	7.253	4.25

Table 1.4.1: Simulation vs theoretical resonances. Source: Original content.

The result obtained has a relatively insignificant relative error, even in the case of seamless cabinet, where the behaviour has been approximated as if it were a square cabinet.

These results endorse the method followed at a theoretical and simulated level as an adequate method with accurate results, although these results must be contrasted with reality to see if the conclusions are finally coherent.

On the other hand, once the resonance frequencies were located, it was necessary to obtain how the field was distributed around the cabinet in order to subsequently locate the material.

Although both magnetic and electric fields are important when determining the resonances, in this work it has been studied the distribution of the magnetic field because it tends to have a clearer distribution, easier to study and more measurable, in addition to the fact that what is sought with the distribution of the field is to know where to locate the absorbing material, which is responsible for absorbing magnetic fields, not electric ones. It is shown in Figures 4.4, 4.5 and 4.6 the distribution of the H field:

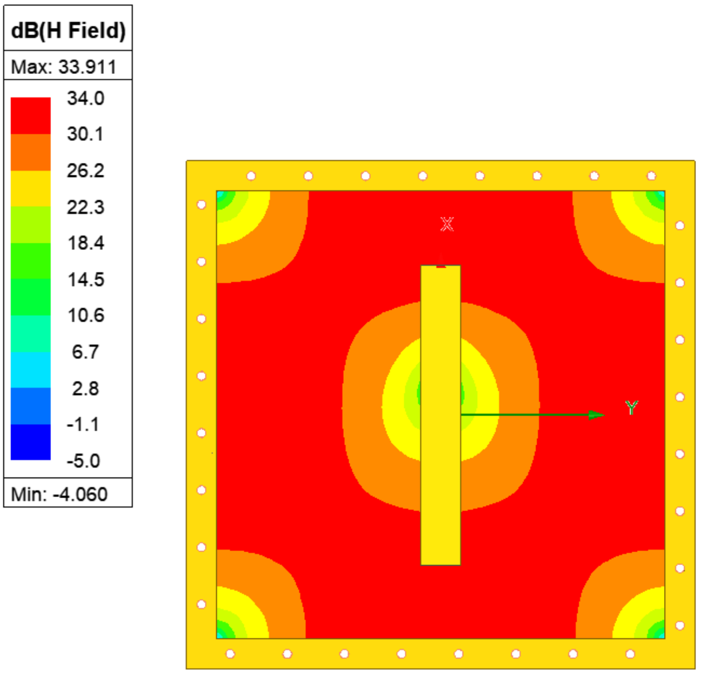

Figure 4.4: Standard cabinet H field distribution. Source: Original Source

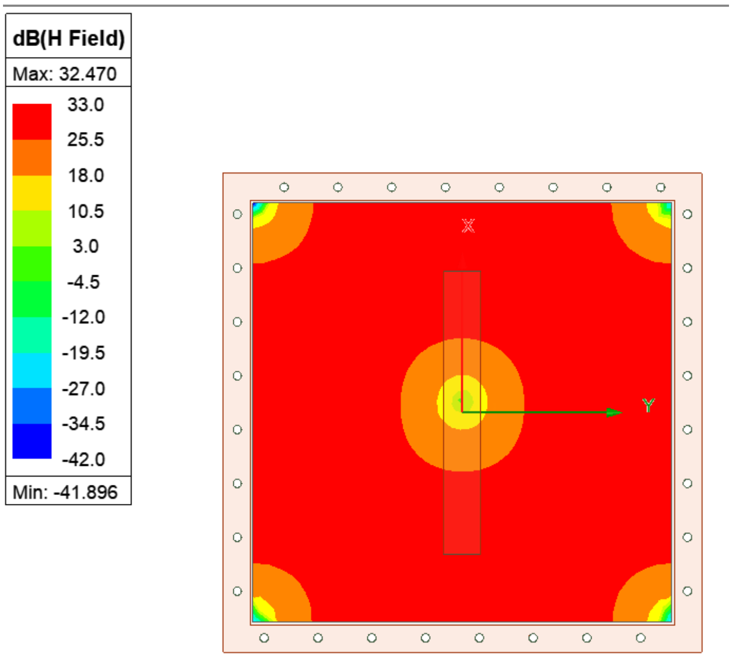

Figure 4.5: DIY H field distribution. Source: Original Source

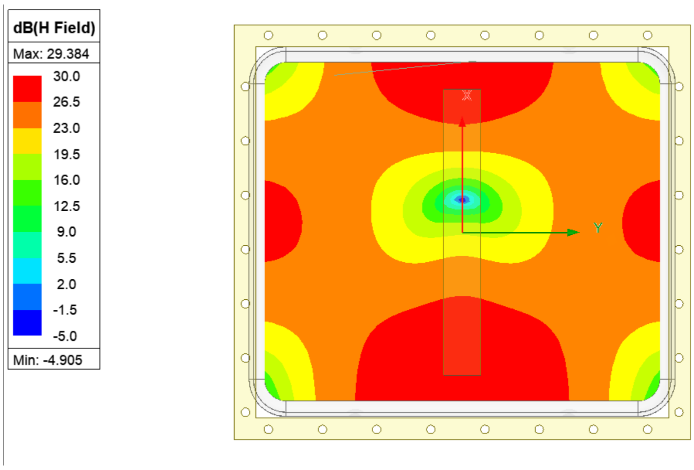

Figure 4.6: Seamless cabinet H field distribution. Source: Original Source

This is the distribution H field has respectively when resonance occurs within the cabinet. As can be seen, the magnetic field can exceed a value of 30dB (equivalent to 50A/m), which can be very detrimental to the operation of the component.

Furthermore, the distribution coincides in that it tends to be less concentrated in the centre of the lid, and the edges are where its value tends to increase.

It is also common that right at the corners there is less concentration of magnetic field, probably because of the welding (in the case of the seamless) or because of the small holes in the cabinet (in the case of the other two) the field in that place, instead of being reflected, is radiated away from the cabinet.

These distributions will determine the location of the WE-FAS TC when the actual tests are carried out.

2 Shielding test results

2.1 Tested cavity resonances

Figure 4.7 shows a picture of the setup for the measurements. As can be seen, the cabinet is embedded in the PCB and the two wires respectively connect the ends of the microstripline with the network analyser:

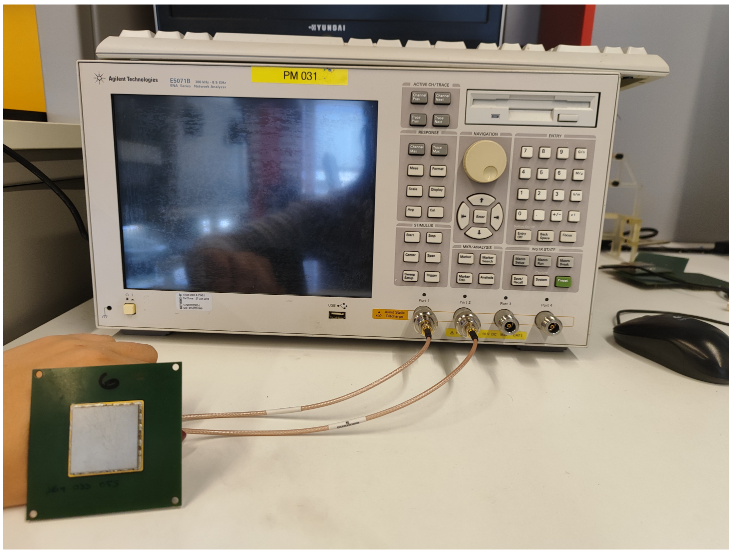

Figure 4.7: Final setup. Source: Original Source

In this case there is no absorbing material inside the cabinet, so the parameter S21 will be measured, which will indicate if there is transmission from port one to port two. Theoretically there should be continuous transmission, and if there is any attenuation it would indicate that there are interference problems there, that is, a cavity resonance.

Before making this measurement, it should be done first a measure to have a reference of how the signal evolves without a cabinet and this is the signal that should not be modified. Figure 4.8 shows the graph of parameter S21 of the microstripline when there is no cabinet in place:

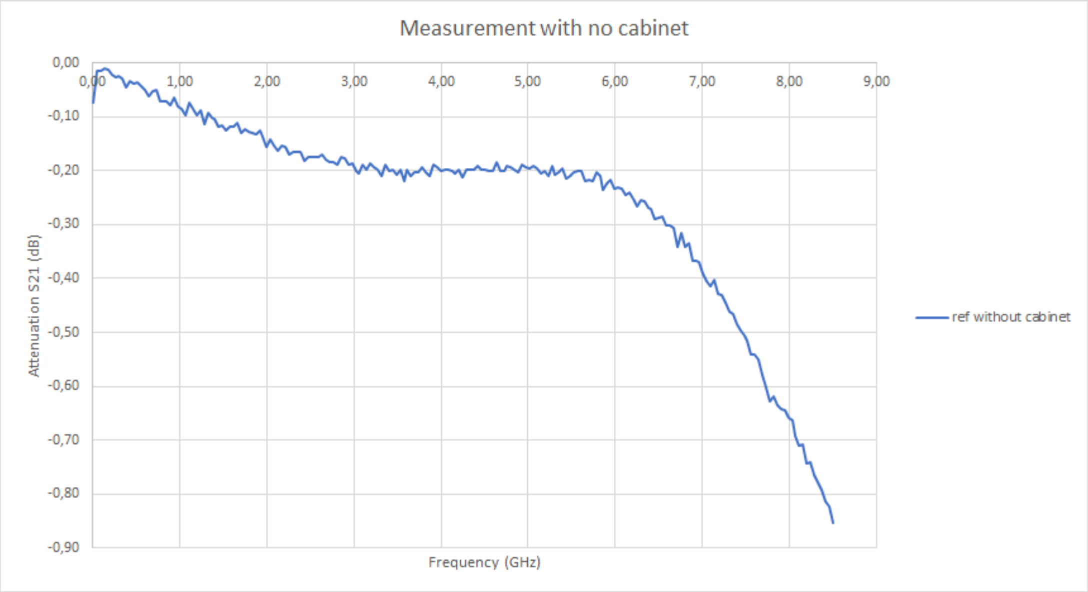

Figure 4.8: Parameter S21 of the microstripline. Source: Original Source

The most linear behaviour is up to 5 GHz, that is the maximum transmission point of the antenna and after that there is a little downward trend but practically imperceptible (less than 1 dB). This signal will serve as a basis to see what modifications the cabinet will undergo.

Figures 4.9, 4.10 and 4.11 show the resonances that appear respectively in the standard, seamless and DIY cabinets.

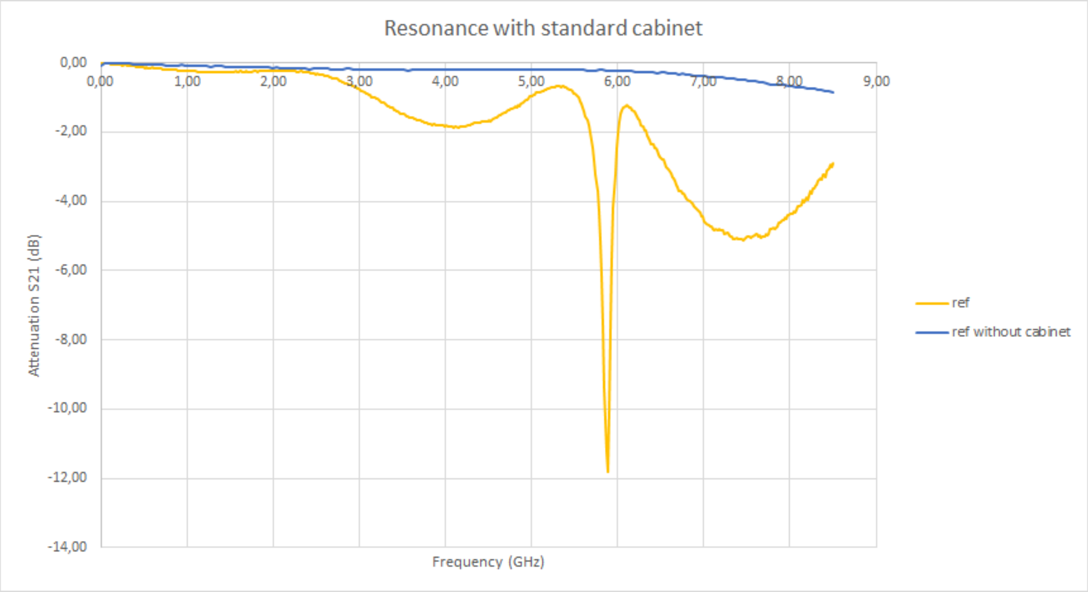

Figure 4.9: Standard cabinet resonance. Source: Original Source

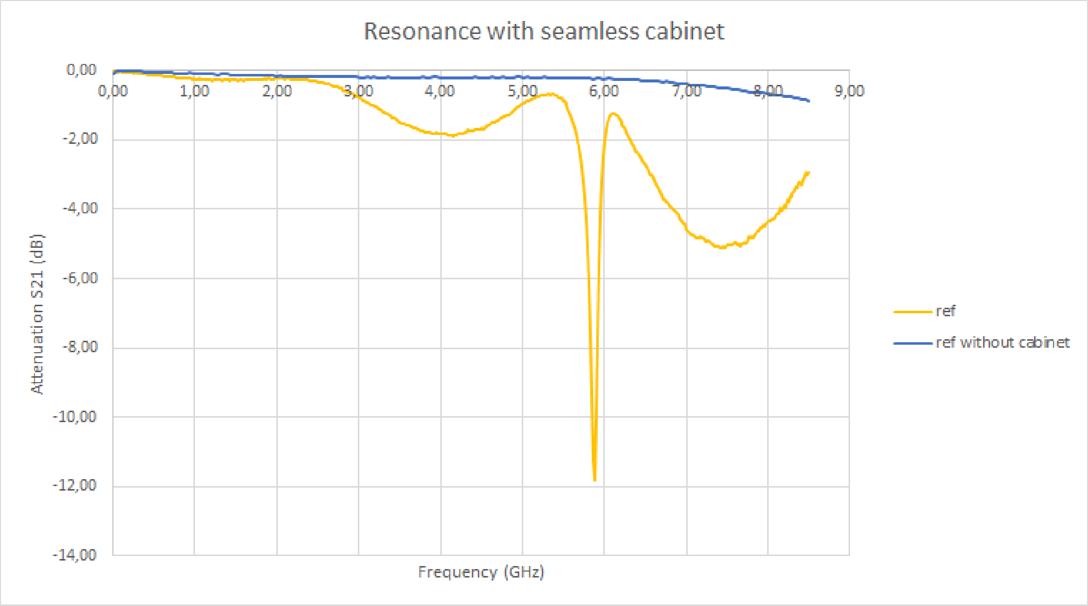

Figure 4.10: Seamless cabinet resonance. Source: Original Source

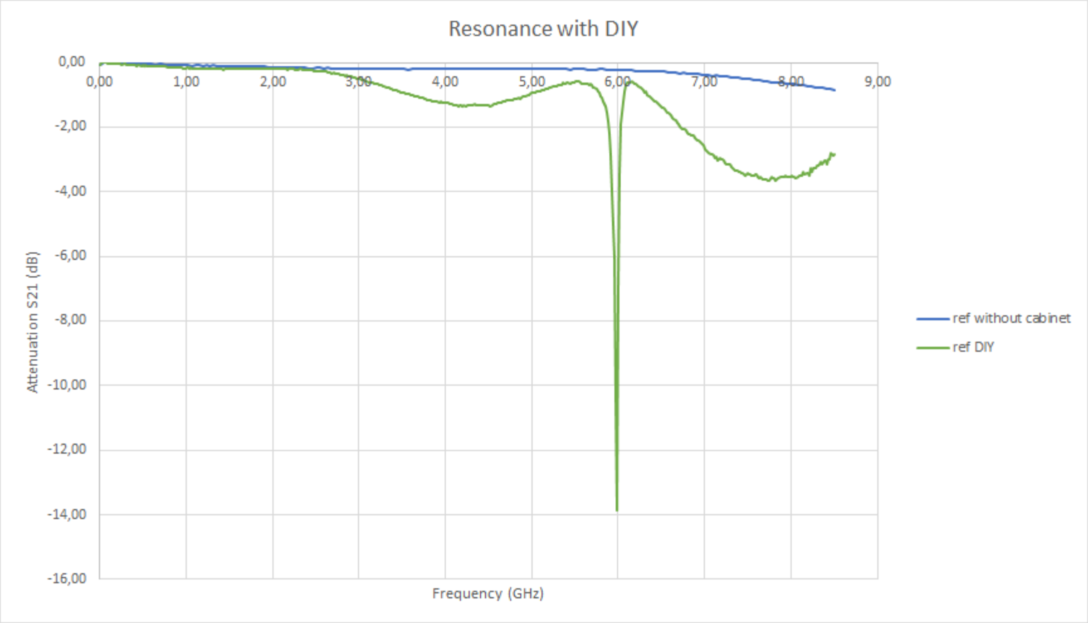

Figure 4.11: DIY cabinet resonance. Source: Original Source

As can be seen, the area of maximum transmission is completely cancelled out with any cabinet in place and a peak attenuation appears, shifted slightly to the right respectively to the peak transmission. It is noteworthy that with the standard and the DIY the attenuation peak is slightly higher than 10 dB while with the seamless the peak exceeds 20 dB.

To see where the resonance peak appears more clearly and precisely, the data is presented in Table 1.4.1:

Cabinet	Tested resonance (GHz)	Theoretical resonance (GHz)	Relative error (%)
Standard	5.88	6.170	4.70
DIY	5.98	6.376	6.21
Seamless	6.34	7.253	12.59

Table 1.4.1: Tested vs theoretical resonances. Source: Original content.

The resonances found in the tests are very similar to those calculated theoretically, which indicates that the formula used is a reliable method for calculating resonances in cabinets of these characteristics.

The one that differs the most, as expected, is the seamless cavity, as the formula is for a perfectly square or rectangular cavity, which is not the case for the seamless cabinet.

It is important to note that the DIY cabinet is a cabinet that is placed by hand and that every time you want to place the material inside it is necessary to redo the cabinet by hand, get a new PCB and solder. All these changes make the measurements unreliable in the last step (including the WE-FAS TC), that's why only materials will be placed inside the standard cabinet and the seamless cabinet, which being of two pieces, in an easy and simple way you can remove the cover of the cabinet and place the desired material.

Beyond the theoretically calculated resonance, it is considered relevant to compare the tested resonance with the simulated resonance, so that it can also be seen whether the simulation method is coherent with the results.

In Table 1.4.2 can be seen the comparion:

Cabinet	Tested resonance (GHz)	Simulated resonance (GHz)	Relative error (%)
Standard	5.88	5.832	0.82
DIY	5.98	6.225	3.94
Seamless	6.34	6.945	8.71

Table 1.4.2: Tested vs simulated resonances. Source: Original content.

What is simulated with what is obtained in reality is even more precise than the comparison between what was tested and what was calculated theoretically. The error in the standard cabinet is practically negligible, again, the error in the seamless, although not as significant as before, is still the highest value as expected.

In general terms, the conclusion is good, what was tested and what was simulated coincides, so the method followed is rigorous and coherent.

2.2 WE-FAS TC placement

As seen in the simulation section, most optimal choice was to place the material in the corners of the cabinet, even so before distributing the material on the outside, we wanted to check if placing a piece of material in the center of the cabinet would also This resonance was attenuated.

This test was started because it was much easier to cut and place the material in the same place as it was a single piece. It could also serve as a good starting point to later compare the best or worst effectiveness of putting the material in the corners.

The FAS-TC has 3 different thicknesses, one, two and three millimeters, so three tests were carried out with the three thicknesses to see if the thickness of the material also affected its effectiveness in absorbing resonance. In Figures 4.12 and 4.13 can be seen the results of the location of these three thicknesses in the respective cabinets by placing a 1x1 mm square in the center:

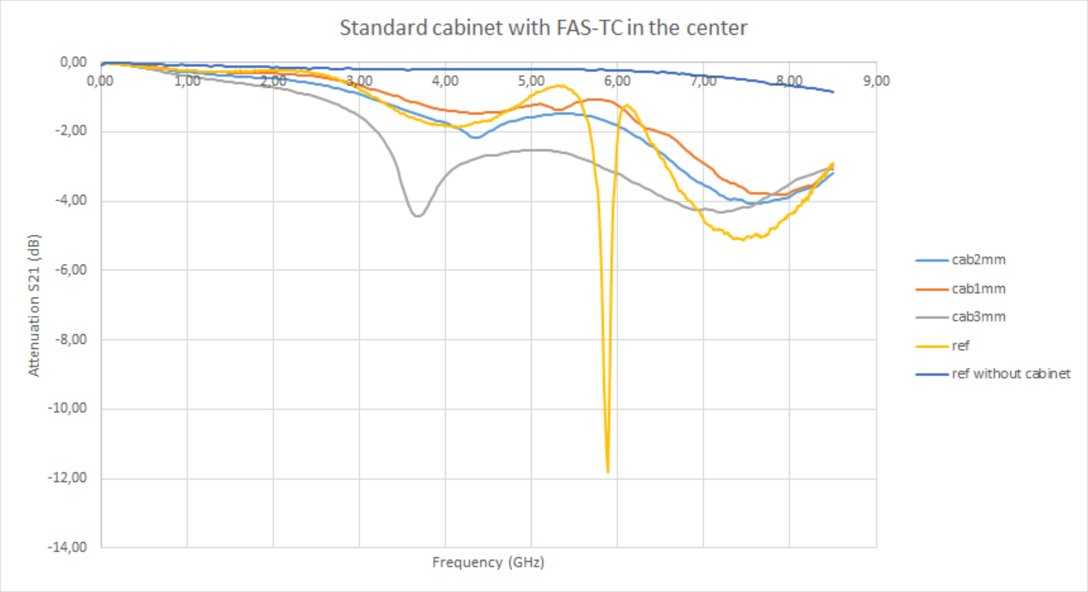

Figure 4.12: Standard cabinet. Source: Original Source

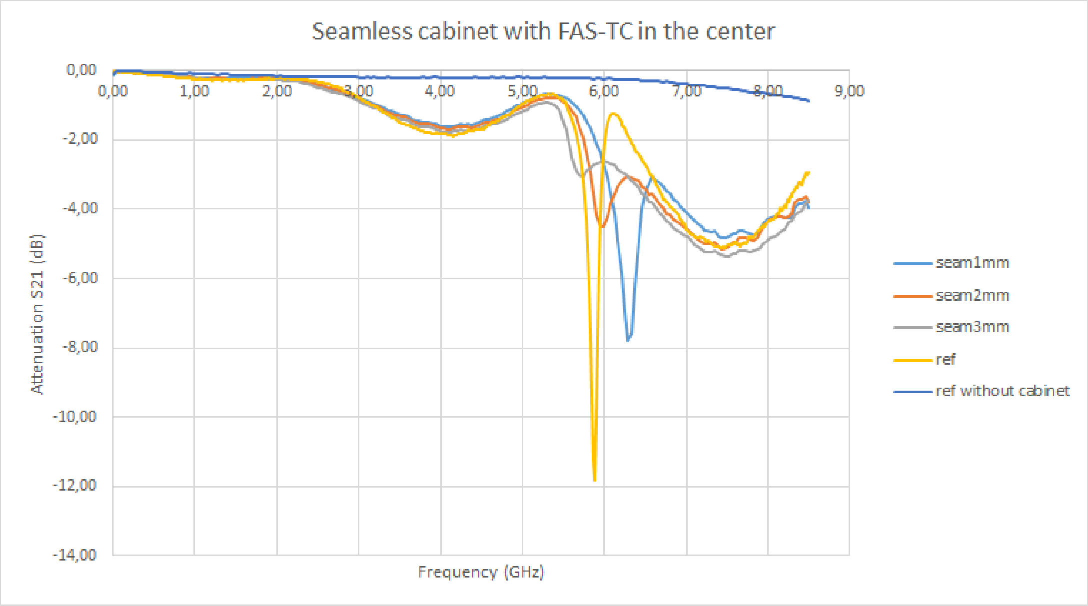

Figure 4.13: Seamless cabinet. Source: Original Source

At first it can be seen that there is a drastic improvement in the level of attenuation by simply placing the material in the center, regardless of the thickness. It goes from having a peak attenuation of more than 10 dB to a maximum of around 4 or 5 dB, that is, more than half of the absorbed attenuation.

Paying attention to the thicknesses, focusing on the 5GHz area which is where the transmission peak should be, in the case of the standard cabinet, both one and two millimeters work very well, achieving 2 dB attenuation at that frequency. In the case of three millimeters it seems that this thickness does not achieve such good performance.

In the case of the cabinet seamless, in the 5GHz area they all present an attenuation very close to zero, although it is true that the 1 mm relocates the peak of resonance at higher frequencies (more than 6GHz) than the other two thicknessess.

It has been demonstrated that it is possible to combat these resonances by placing an absorbing material, however, the location of the material was not optimal according to the simulations and that is why it has been proceeded to place the material where the simulation indicated that the magnetic field was concentrated.

Before presenting the results, it is important to point out two things:

- The amount of material used has been the same, because instead of a piece of one by one millimetre, two pieces of 0.5 by 0.5 millimetres both have been used.
- The location was not exactly at the corners, because if it had been placed there, the cavity would not have been able to be closed.

Figure 4.14 shows the result of applying the different thicknesses to the standard cabinet in the most optimal parts according to the simulation:

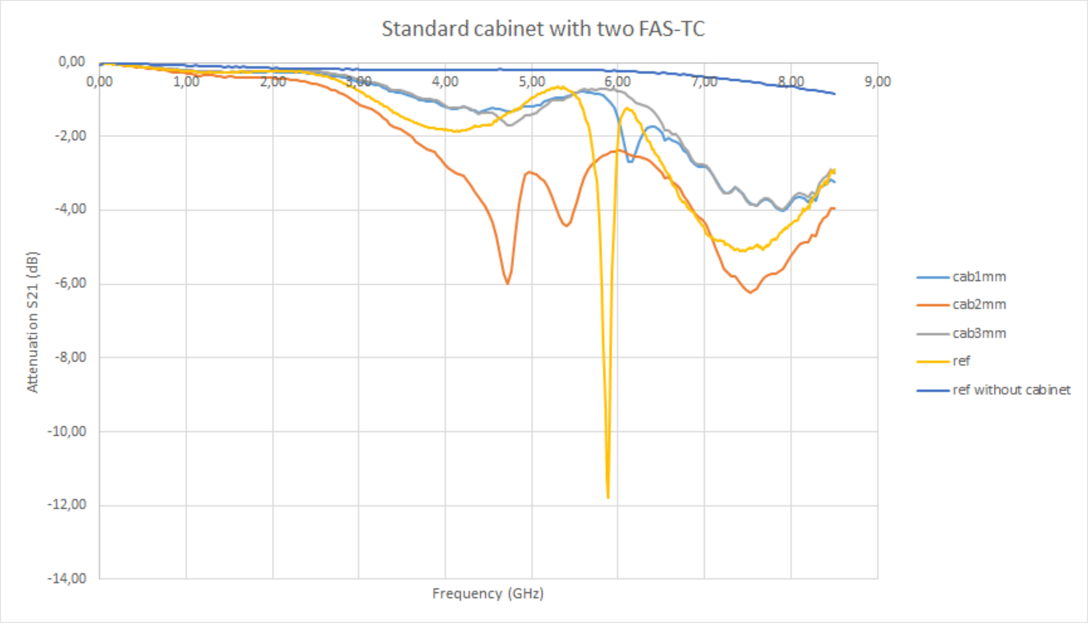

Figure 4.14: Standard cabinet with two pieces. Source: Original Source

In this case, it is observed that the thickness that gives the worst response is the one millimetre thickness, however, at an overall level, the attenuation improvement results are comparable to placing a single piece in the centre of the cabinet.

Figure 4.15 shows the same graph but applied to the seamless cabinet:

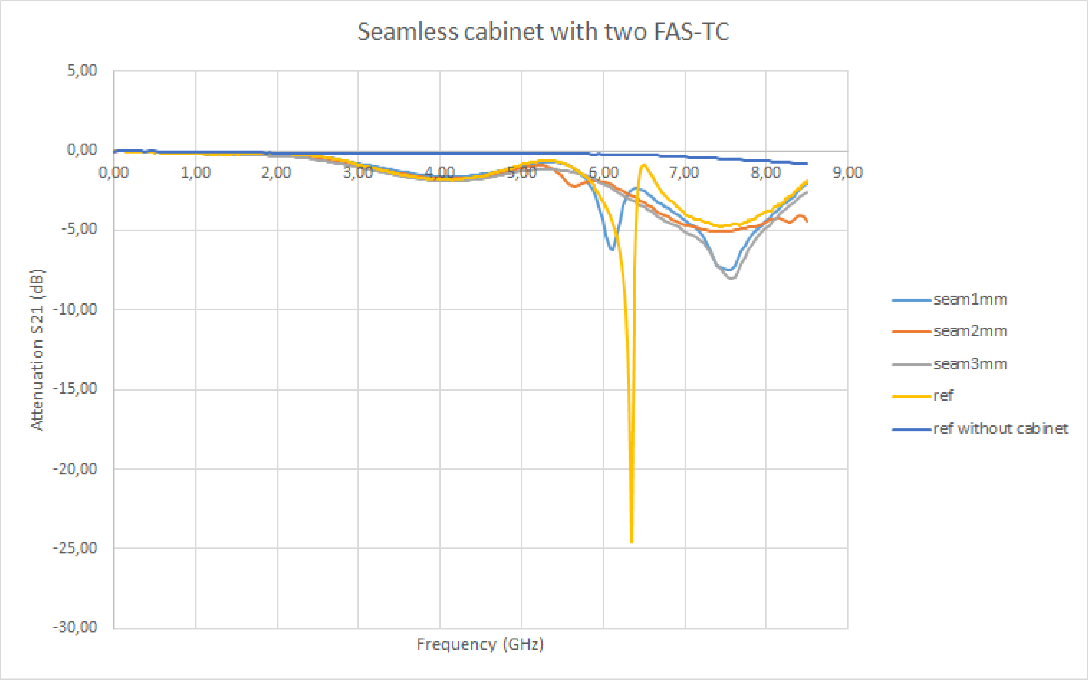

Figure 4.15: Seamless cabinet with two pieces. Source: Original Source

As can be seen, the behaviour is very similar to that observed with a single piece, with the three thicknesses having practically identical performance at the maximum transmission frequency of the microstripline.

In terms of thickness it is not possible to draw conclusive results, on the one hand because depending on the cabinet or distribution it seems that some thicknesses work better than others. And on the other hand, and more relevant, because in order to characterise it well it would be necessary to have data on the permeability and permittivity of the material at high frequencies in order to know its expected behaviour, simulate it and draw conclusions.

3 Thermal test results

For the thermal tests, a resistor with 5W power rating up to 70ºC, more than 4W at 80ºC and 50ohm resistance was used, which, as described in the thermal setup section, was soldered to the microstrip PCB and subjected to a certain power to see the evolution of the temperature of the resistor.

As an initial point, the sensor is placed on top of the resistor, but once the cabinet is located, the sensor is placed right on the cabinet lid.

Starting from this base, two tests have been carried out. The first has subjected the resistance to a power of 1.6W and waited for it to reach 80 degrees. Having measured the time it took to reach that temperature, the resistance was subjected to that same time with the cabinet on (both with the material and without it), to see if the temperature increased more with the material on.

The second has subjected the resistance to a power of 0.9W, when the temperature of the resistance has been stabilized and the setup was left for more than twenty minutes in those conditions to ensure that the temperature did not vary. The cabinet was then placed with and without material for fifteen minutes respectively to see the heat transfer over a longer range of time.

A break was taken between tests with and without material in the cabinet, allowing the resistor to return to room temperature between tests. As can be seen, the resistance was never subjected to the maximum possible power, since what was sought was for it to reach a temperature range high enough to appreciate the increase in temperature but without putting the operation of the resistance or excessive overheating.

In Table 1.4.1, can be found the summary of the first test:

Parameters	**Data**
Voltage	4V
Amps	0.4A
Initial Temperature	29 degrees
Final Temperature only resistor	80 degrees
Final Temperature top of the cabinet	33 degrees
Final Temperature top of the cabinet with material	35.8 degrees
Time per test	1 min 12 seconds

Table 1.4.1: Thermal test 1. Source: Original content.

In the time indicated in the table, depending on whether or not there was material inside the cabinet, you can see the variation in the temperature increments that is recorded in Table 1.4.2:

Setup	**Temperature increase**
Only resistor	51 degrees
With the cabinet	4 degrees
With the cabinet and FAS-TC	6.8

Table 1.4.2: Thermal test 1 increase of temperatures. Source: Original content.

In such a short time you cannot perceive a big difference between applying material and not applying it, although you can already perceive an increase of a couple of degrees of difference between placing the material and not doing so.

For this reason, the second test lasting fifteen minutes is carried out, where from a stable temperature the increase in temperature is seen with and without material in the cabinet with more time. Table 1.4.4 shows the test parameters:

Parameters	Data
Voltage	3V
Amps	0.3A
Initial Temperature	28.2 degrees
Final Temperature only resistor	64.5 degrees
Final Temperature top of the cabinet	36.2 degrees
Final Temperature top of the cabinet with material	39.7 degrees
Time per test	15 minuts

Table 1.4.3: Thermal test 2. Source: Original content.

It is important to note that after minute 7 or 8 the temperatures of the cabinets stabilized, so even if the test had been left to run for more than 15 minutes, the temperature increase would not have changed.

Table 1.4.4 shows the temperature increases obtained:

Setup	Temperature increase
Only resistor	36.3 degrees
With the cabinet	8 degrees
With the cabinet and FAS-TC	11.5 degrees

Table 1.4.4: Thermal test 2 increase of temperatures. Source: Original content.

With these results and using the Fourier equation:

$$Q = \frac{k * A * (T2 - T1)}{d} \tag{4.1}$$

the heat flows with and without material can be obtained to analyse if indeed replacing the air gap between the cabinet and the resistor with FAS-TC material favours the heat exchange.

In order to calculate the heat exchange, the following values have been put into the Fourier equation:

- k of the air: 0,0026 Wm-1 k-1
- k of the FAS-TC: 1.4
- Area of the resistor: 5,5e-5
- Area of the FAS-TC: 2,5e-5 m2
- Distance: 5 mm (height of the cabinet)
- Temperature increase: obtained from Table 1.4.4

The results are shown in Table 1.4.5:

Setup	Heat Flow (mW)
With the cabinet	2.3
With the cabinet and FAS-TC	81

Table 1.4.5: Heat flow. Source: Original content.

As can be seen, positioning the material increases the heat flow by more than 350 times.

4 Conclusion

For this section it is considered relevant to remember the main objectives of this work:

- To identify by means of simulations with Ansys software and theoretical calculations the resonant cavities of different types of WE cabinets.
- To identify by testing if the resonances found in the simulations coincide with what happens in reality.
- Simulate and test the application of WE-FAS TC as a mitigator of these resonances.
- Test the impact of the thermal properties of WE-FAS TC.

The first two points are considered fulfilled since with respect to the theoretical values, the simulations in Ansys do not deviate by even seven percent and neither do what is obtained in the laboratory, so the methodology and results obtained are satisfactory and precise.

The WE-FAS TC product represents a very significant improvement in the reduction of resonance peaks obtained inside the cabinet, with jumps that go from 25dB of resonance to less than 5dB thanks to incorporating the material.

Finally, regarding the thermal part, although an increase in thermal flux is shown thanks to the material, the temperatures obtained, the reduced testing area and the little depth in this topic mean that it is not considered conclusive whether the use of the material would mean really a significant improvement in thermal management.

It is important for this author to emphasise the importance of this work for the company Würth Elektronik. On the one hand, it has been successfully demonstrated that the WE-FAS material can attenuate resonances, which opens up a world of possibilities for shielding electromagnetic sealing problems in PC or other electronic applications.

On the other hand, thanks to the combination of the material in the cabinet lid, the application field of shielding cabinets has been extended, as they can now be used in applications operating at frequencies above 5GHz.

For future research, it would be of great importance to use a more precise numerical method to calculate the resonances in seamless cabinets, since these, being rounded and not square, were the ones that presented the most deviations.

Furthermore, characterizing the absorbing material at high frequencies can be differential to simulate the attenuation of resonances at different thicknesses and positions and not only base it on the experimental method.

Finally, the work has involved a satisfactory personal effort, allowing the author to delve into topics not covered in the degree such as simulations and at the same time settle knowledge obtained during the studies.

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