ImpEMItrable: Testing Materials and Gasket Shielding Abilities in Building a Faraday's Box

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Abstract
In past studies of EMI shielding, still a developing field, much focus was placed on RFID shielding, which mostly included attenuation of high-frequency signals with the intention of blocking cell tower and WiFi signals, both common mediums through which MiTM (Man in the Middle) attacks occur. Furthermore, Faraday's Box material studies are often favoured to gaskets, which remain an important study in preventing EMI leakages, In this study, low-frequency EMI shielding and using gaskets to seal gaps in a Faraday's box was investigated with a variation of materials and gaskets. Through simulations done with CST and with actual experiment measurements, we intend to find an optimal combination of both enclosed materials and gaskets e to produce a lightweight, low-cost Faraday's Box that is able to expand its shielding effectiveness beyond the high-frequency (1.0 GHz - 10.0 GHz) range. From our experiments, we propose a Faraday's box construction of a hybrid layer of Mu-metal and Trans-polyacetylene with the use of neodymium magnets and chromium rubber as a hybrid gasket to seal the box. To further reduce the density of the box, Mu-metal flakes could be injected into Trans-polyacetylene plastic moulds.

Introduction

Advancements in technology have made it easier for those with malicious intent to hack into devices and steal sensitive information through electromagnetic radiated emissions means. As a result, cyberattacks have expanded beyond espionage to private settings and there is a greater need to protect and prevent the risk of sensitive information from being stolen via electromagnetic means.

A common way to increase protection against such electromagnetic leakage is the use of shielding enclosures. A Faraday's Box is an enclosure, formed by continuous covering of conductive material, that shields off electromagnetic (EM) fields. Metals like aluminium and copper are commonly used to build Faraday's Boxes due to their high electrical conductivity, with copper as the second-highest metal electrical conductor of 58Ms/m at 20 degrees Celsius [1] and aluminium with 61% the electrical conductivity of copper. [2] However, these metals are heavy and are prone to corrosion. Furthermore, research has found that while aluminium and copper have high shielding effectiveness at higher frequencies (≥ 10MHz), [3] their shielding ability seems limited at lower frequencies (< 10Hz). On the other hand, Mu-metal which is formulated specifically for low-magnetic fields at frequencies smaller than 1MHz, is not commonly used due to its high costs. While there have been studies on the layering of metals, [4] there is a lack of research on the layering of Mu-metal with other metals to maximise shielding effectiveness over a wider range of frequencies. Hence, we wish to compare the shielding effectiveness of the different combinations with Mu-metal with varying thickness.

In addition, the use of seals have been found to greatly increase shielding effectiveness of Faraday's Boxes and prevent any leakages. [5, 6] However, commonly found seals, like flange gaskets and aluminium tape, are often either heavy, highly inconvenient to use or not reusable. In comparison, magnetic seals are much more user-friendly while conductive fabric shielding gaskets (FSG) and rubber seals are more lightweight. Thus, in this paper we compared the shielding effectiveness of different combinations of neodymium magnets with various rubber and foam materials to form a reusable and user-friendly hybrid gasket.

Recent developments in RFID shielding have shown commercialised products such as Faraday bags and Faraday pouches sold by companies like Offgrid and Disklabs, which prevent RF signals from being transmitted to and by your phone. They are made using conductive fabric lined with metal mesh, which are porous materials that are flexible and relatively more lightweight in comparison to their alloy sheets. There have also been recent studies of injecting metal flakes into plastic moulds to create conductive polymers that retain the electrical and magnetic properties of the metals while greatly reducing the density of the metals. Such a method is also far more cost-efficient, though yet to be introduced for commercial uses due to insufficient research.

Our hypothesis is that the combination of copper and Mu-metal along with the combination of neodymium magnets and FSG would be the most effective in shielding EM waves. The goal of our research is to find the most cost-sensitive yet effective methodology of creating a Faraday's Box, such that it can provide sufficient security while maintaining its cost effectiveness and lightweight.

Materials and Methods

The research was conducted in 2 parts - Simulations and actual physical measurements.

Simulation

Gaskets and various shielding box materials were used in our simulations. Our criteria for the gaskets were that they should be reusable, easy to use and lightweight. As for the shielding box materials, they should be lightweight, low-cost and have a shielding effectiveness of at least 40 dB.

Simulations involving the frequency ranges of 1.0 MHz - 1.0 GHz were conducted with the addition of a magnetic gasket, fabric shielding gasket (FSG) and different rubber gaskets to an aluminium box as well as the combination of magnetic gaskets with FSG and different rubber gaskets. The materials used consist of neodymium magnets, polyurethane foam with nickel ripstop fabric, acrylonitrile butadiene rubber (NBR), chloroprene rubber (CR) and silicone rubber (SR). The specifications for gasket materials can be found in Figure 1.

Chloroprene Rubber (CR)	
Type	Normal
Mu	1.1
Epsilon	6.7
Electric conductivity (S/m)	0
Density (kg/m^3)	1325
Thermal conductivity (W/K/m)	0.175
Specific heat capacity(J/K/kg)	2200
Diffusivity (m^2/s)	6.00343e-08

FSG Gasket (Polyurethane Foam with nickel ripstop fabric)	
Type	Normal
Mu	2.3025e-14
Epsilon	2.5
Electric conductivity (S/m)	1.44e+007
Density (kg/m^3)	425
Thermal conductivity (W/K/m)	0.0576
Specific heat capacity(J/K/kg)	1200
Diffusivity (m^2/s)	1.12941e-07

Silicone Rubber (SR)	
Type	Normal
Mu	35
Epsilon	3.45
Electric conductivity (S/m)	0
Density (kg/m^3)	2250
Thermal conductivity (W/K/m)	3.28
Specific heat capacity(J/K/kg)	790
Diffusivity (m^2/s)	1.84529e-06

Acrylonitrile butadiene rubber (NBR)	
Type	Normal
Mu	5
Epsilon	10
Electric conductivity (S/m)	0
Density (kg/m^3)	116
Thermal conductivity (W/K/m)	0.245
Specific heat capacity(J/K/kg)	1950
Diffusivity (m^2/s)	1.08311e-06

Magnetic Gasket (Neodymium)	
Type	Lossy metal
Mu	1.05
Electric conductivity (S/m)	6.67e+005
Density (kg/m^3)	7500
Thermal conductivity (W/K/m)	8.9551
Specific heat capacity(J/K/kg)	0.5024
Diffusivity (m^2/s)	0.00237662
Young's modulus (kN/mm^2)	160
Poisson's ratio	0.24
Thermal expansion (1e-6/K)	7.5

Figure 1: Specifications of different Gasket Materials

In the model used, a plane wave (550.5Mhz) was generated to propagate in the negative z-direction towards the aluminium box and a field monitor was placed within the box to measure the shielding effectiveness of the gasket at a fixed point. The second layer was replaced with various gasket materials. For the hybrid gasket setup, two different layers of gasket materials were used, with the thickness of the gasket layer kept constant.

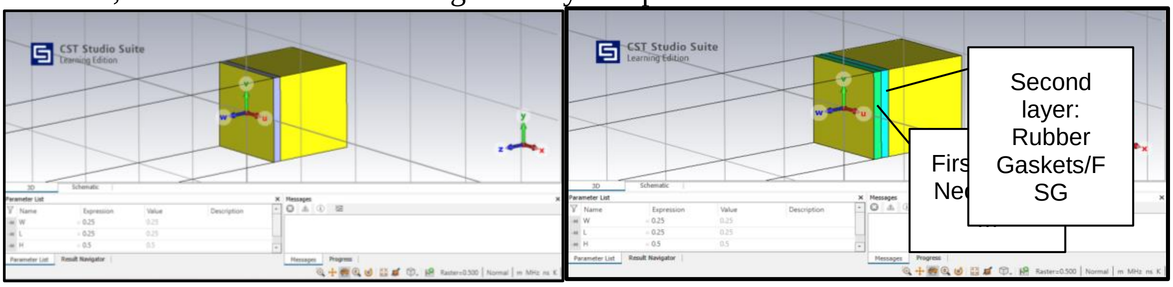

Figure 2.1-2.2 (From left to right): CST Test Setup for single gasket/hybrid gaskets

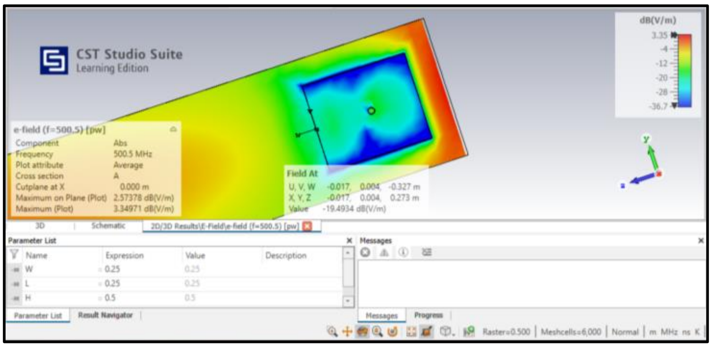

Figure 2.3: Sample Cutting Plane of Aluminium Box in 2D/3D Results

Simulations involving the frequency ranges of 1.0 kHz to 1.0 GHz were also conducted using various materials that could potentially be used for a Faraday's box. Conductive polymers Polyaniline (thin film), Polypyrrole (thin film), Trans-polyacetylene (doped) and Polythiophene (doped) were used in the simulation, inspired by recent developments in materials science that has found a lightweight, low-cost substitute to metals that retain a high electrical conductivity. Flexible graphite and Mu-metal were used as simulation materials as well. Copper and aluminium were not used, as its material type as a Lossy Metal causes it to have an extremely high electrical conductivity, where shielding effectiveness is infinite by theory. The specifications for the materials used in simulations can be found in Figure 3.

Polypyrrole	
Type	Normal
Mu	1
Epsilon	30
Electrical conductivity (S/m)	38000
Density (kg/m^3)	1500
Thermal conductivity (W/K/m)	0.2
Specific heat capacity (J/K/kg)	400
Diffusivity (1e-06 m^2/s)	0.333333
Young modulus (kN/mm^2)	9.5
Poisson's ratio	0.40

Trans-polyacetylene	
Type	Normal
Mu	1
Epsilon	5.7
Electrical conductivity (S/m)	3800
Density (kg/m^3)	400
Thermal conductivity (W/K/m)	0.8
Specific heat capacity (J/K/kg)	1750
Diffusivity (1e-06 m^2/s)	1.14286
Young modulus (kN/mm^2)	27
Poisson's ratio	0.30

Polyaniline	
Type	Normal
Mu	1
Epsilon	100
Electrical conductivity (S/m)	194
Density (kg/m^3)	1329
Thermal conductivity (W/K/m)	0.6
Specific heat capacity (J/K/kg)	400
Diffusivity (1e-06 m^2/s)	1.12867
Young modulus (kN/mm^2)	1.3
Poisson's ratio	0.30

Mu-metal	
Type	Normal
Mu	350000
Epsilon	88.54
Electrical conductivity (S/m)	65000
Density (kg/m^3)	8700
Thermal conductivity (W/K/m)	19
Specific heat capacity (J/K/kg)	460
Diffusivity	4.74763
Young modulus (kN/mm^2)	225
Poisson's ratio	0.29

Graphite	
Type	Normal
Mu	1
Epsilon	12
Electrical conductivity (S/m)	100000
Density (kg/m^3)	2250
Thermal conductivity (W/K/m)	24
Specific heat capacity (J/K/kg)	710
Diffusivity (1e-06 m^2/s)	15.0235
Young modulus (kN/mm^2)	4.8
Poisson's ratio	0.20

Polythiophene	
Type	Normal
Mu	1
Epsilon	6
Electrical conductivity (S/m)	1860
Density (kg/m^3)	1066
Thermal conductivity (W/K/m)	0.5
Specific heat capacity (J/K/kg)	1320
Diffusivity (1e-06 m^2/s)	0.355336
Young modulus (kN/mm^2)	4
Poisson's ratio	0.35

Figure 3: Specifications for Various Faraday's Box Materials

There were parameter changes from 1.0 kHz to 1.0 MHz, 1.0 MHz to 200 MHz and 300 MHz to 1.0 GHz, where the dimensions were altered from 200mx200mx0.01m, 0.845mx0.845mx0.0001m and 0.15mx0.15mx0.0001m respectively. The boundaries and probe points were adjusted according to the scale factor of the changes. This was done in order to minimise the mesh size of the setup, ensure that the size of the panels were at least larger than 1/10th of the wavelength of the plane wave as determined by its frequency (assuming EMI travels at the speed of light in the simulation), and account for the skin depth of the material. This is to ascertain the validity of the shielding effectiveness of the material at various frequencies as EMI fields may not be blocked at the material's maximum effectiveness if the panel size is smaller than 1/10th of the wavelength of the plane wave. The materials were first tested individually to identify the top three materials with the best shielding effectiveness. Thereafter, the three identified materials were tested in combinations with layered permutations of length three. It has been shown that there is an impact on the overall shielding effectiveness if the materials were layered differently. [7]

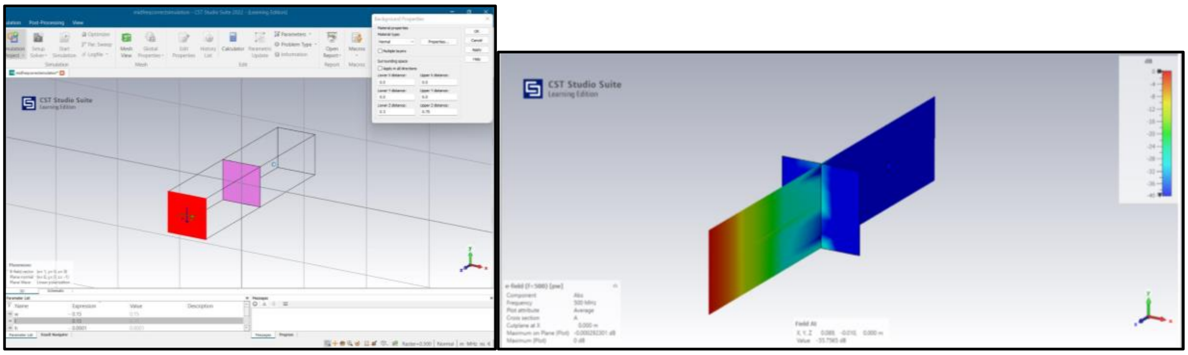

Figure 4.1-4.2 (From left to right): CST Test Setup for single/hybrid material testing (300MHz - 1.0 GHz) and Sample of 2D/3D Plot Results (Mu-metal)

Actual Physical measurements

The shielding effectiveness of the gaskets and shielding box materials were tested using an anechoic chamber, involving the frequency ranges of 30.0 MHz - 1.0 GHz. A signal source was generated using an RF Signal Generator, amplified and fed to the transmitter antenna which was placed outside the anechoic chamber. The receiver antenna was placed inside the anechoic chamber and a spectrum analyser was connected to the receiver antenna to measure the received signal. In this experiment, an aperture was covered using a panel of the shielding material under test and a signal was passed through it to measure the power received in order to calculate its shielding effectiveness.

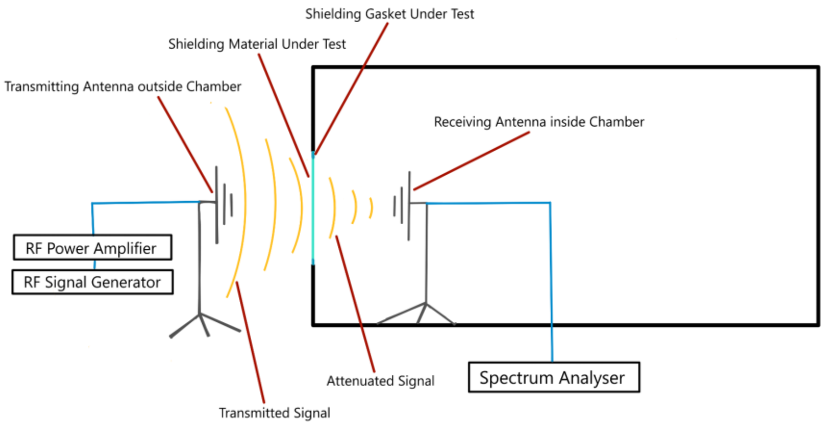

Figure 5: Model of Set Up Used

The measurement started off with Copper panel (0.2mm and 0.5mm thick), Aluminium panel (0.2mm and 0.5mm thick) and Mu-metal panel (0.25mm thick). Thereafter, FSG and Neodymium magnet gaskets were measured with the accompanying Mu-metal panel, as its magnetism would ensure that neodymium magnets would be a suitable gasket to test. The rubber gaskets and conductive polymer/graphite shielding materials were not tested due to resource constraints in obtaining the materials, and the latter more so due to the inability to synthesise the materials in the lab since the polymers were not sold commercially.

Figure 6.1: Example of Aperture being covered with a Mu-metal Panel

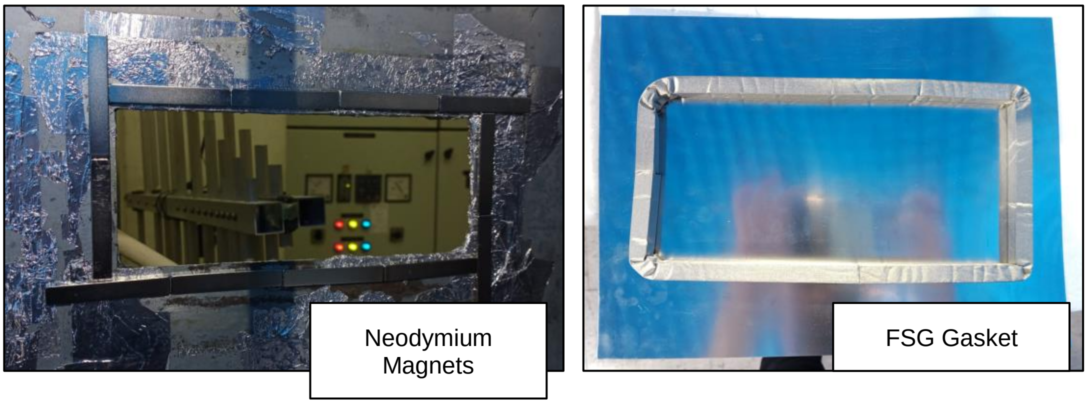

Figure 6.2: Addition of Gasket Materials

To calculate the shielding effectiveness (SE), the following equations were used:

$$SE = Signal\ Strength\ received\ without\ panel\ (air) - Signal\ Strength\ received\ with\ Panel$$

and $SE = 10log(P1/P2)$—-------------------- (Equation 1)

We had previously attempted to conduct another physical experiment using an aluminium Faraday's box, with an electric field probe. However, this experiment was unsuccessful as the shielding effectiveness results obtained using this setup were very similar for all the materials tested across the frequency ranges. This is inconsistent with the results from the experiment carried out in the Anechoic Chamber and the Simulations, which we expected to see a distinct difference in shielding effectiveness between the materials tested. It is suspected that this is largely due to the limitation of the equipment itself, where the range of electric fields that the probe was able to detect and measure were limited and were unable to display the extremely low electric fields that were within the Faraday's Box.

Results

<u>Simulation</u>

The simulation results revealed that the rubber gaskets are having similar shielding effectiveness at the frequency of 550.5MHz, the midpoint frequency of the range 1.0MHz to 1.0GHz. It can also be seen that the combination of the various rubber and neodymium magnets are effective in increasing the shielding ability of the gasket. For the hybrid gaskets, the combination of Neodymium and Chromium Rubber achieved the highest shielding effectiveness of 21.7641dB. Unfortunately, the shielding effectiveness of the magnetic gasket and the FSG gasket on their own could not be quantified as these materials have extremely high electrical conductivity which causes the simulated shielding effectiveness to be infinite in CST.

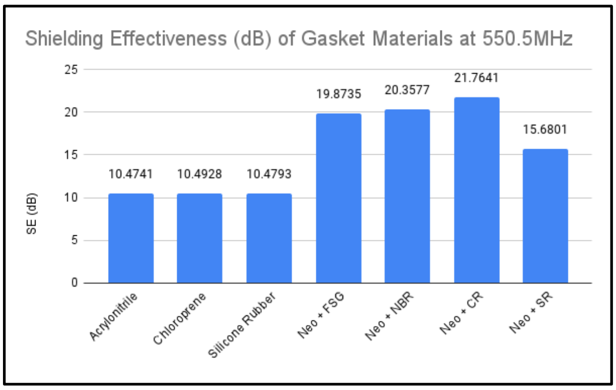

Figure 7: Graph showing the Shielding Effectiveness of various gasket materials and their combinations at a frequency of 550.5MHz

For materials, the simulations show that polyaniline and Mu-metal have weaker shielding effectiveness compared to the other materials at the higher frequency range of 1.0 MHz to 1.0 GHz. Graphite, Trans-polyacetylene and Polypyrrole, which performed the best out of all the materials, were tested as combinations and while their shielding effectiveness from 1.0 MHz to 200.0 MHz were relatively similar, their shielding effectiveness from 300 MHz to 1.0 GHz visibly shows the Polypyrrole/Trans-polyacetylene or Trans-polyacetylene/Graphite having the highest shielding effectiveness. The highest shielding effectiveness in the 1 MHz - 200.0 MHz range was 153.14 dB at 140 MHz, from the Graphite/Polypyrrole combination (though all combinations were roughly similar) and the highest shielding effectiveness in the 300 MHz - 1.0 GHz range was 83.75 dB at 800 MHz, from Trans-polyacetylene. Table 7.1 and 7.2 shows the summarised shielding performance results.

Material	Mean SE for 1.0 MHz - 200 MHz	Mean SE for 300 MHz - 1000 MHz
Mumetal	91.085	64.552
Graphite	123.043	66.068
Polyaniline	60.506	56.383
Trans-polyacetylene	123.921	68.512
Polythiophene	114.294	57.987
Polypyrrole	125.746	64.711
Graphite/P-acetylene	125.158	65.126
P-acetylene/Graphite	124.412	67.088
Graphite/P-pyrrole	126.000	61.327
P-pyrrole/Graphite	125.882	61.302
P-acetylene/P-pyrrole	124.335	65.343
P-pyrrole/P-acetylene	125.071	67.227

Material	Mean SE for 1.0 kHz - 900 kHz
Mumetal	50.100
Graphite	40.849
Polyaniline	42.213
Trans-polyacetylene	43.678
Polythiophene	37.393
Polypyrrole	41.373
Mu/P-acetylene	37.937
P-acetylene/Mu	50.736
Mu/P-aniline	50.753
P-aniline/Mu	50.239
P-acetylene/P-aniline	45.849
P-aniline/P-acetylene	41.373

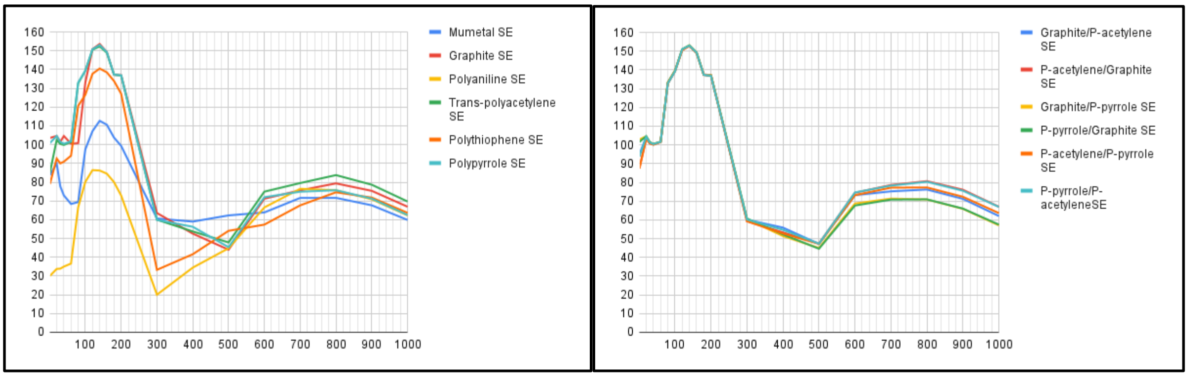

Figure 8.1-8.4: Graphs and Tables showing the Shielding Effectiveness of various shielding materials and their combinations at a frequency range of 1.0MHz to 1.0GHz

For the frequency range of 1.0 kHz to 1.0 MHz, the simulations show that polythiophene consistently had a weaker shielding effectiveness compared to the other materials. Polypyrrole's shielding effectiveness, while having the lowest average, fluctuated the most and had a high shielding effectiveness at certain frequencies. Mu-metal, Trans-polyacetylene and Polyaniline, which performed the best out of all the materials, were tested as combinations. The Polyaniline/Mu-metal combination visibly had the highest shielding effectiveness among the combinations, also having the highest shielding effectiveness of all the tested materials of 64.375 dB at 300 kHz.

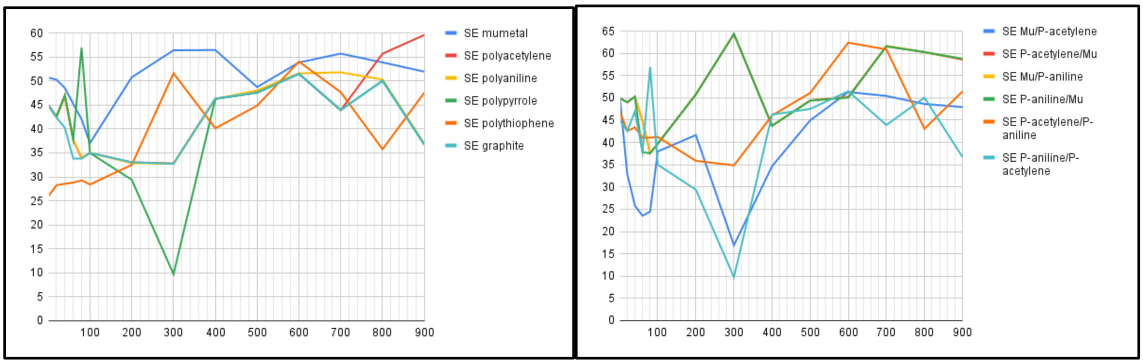

Figure 9: Graphs showing the Shielding Effectiveness of various shielding materials and their combinations at a frequency range of 1.0 kHz to 900.0 kHz

<u>Actual measurement</u>

Both the FSG and neodymium magnets performed better at higher frequencies but this is suspected to be because of the stronger shielding effectiveness of the Mu-metal panel at higher frequencies. In general, while both gaskets showed similar results, the shielding effectiveness of neodymium magnets is slightly higher than FSG.

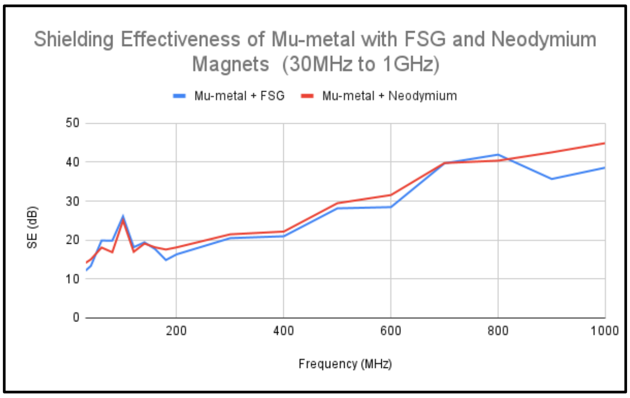

Figure 10: Graph showing the Shielding Effectiveness of Mu-metal with FSG and Neodymium Magnetic Gasket at a frequency range of 30MHz to 1GHz

At the lower frequencies, the shielding effectiveness of Mu-metal was much higher than copper and aluminium, which showed rather similar results despite their different thicknesses. Copper's shielding effectiveness was higher at higher frequencies around the 500 MHz mark.

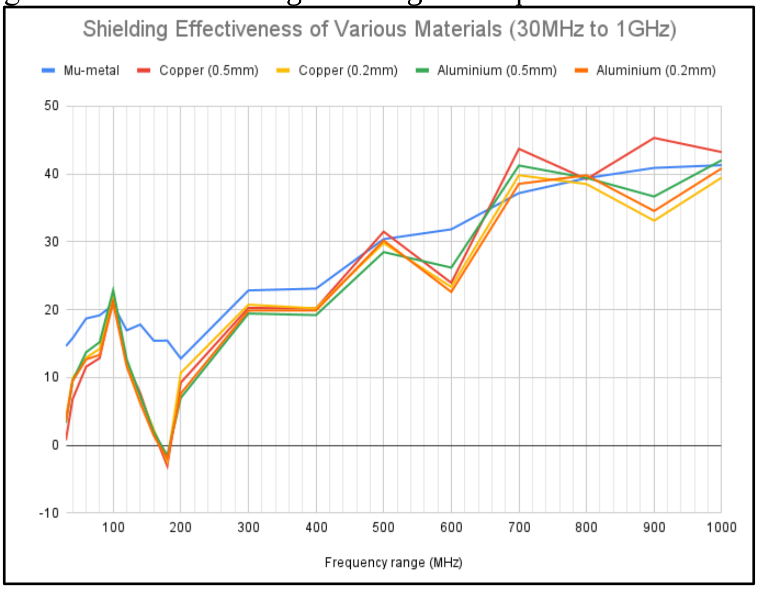

Figure 11: Graph showing the Shielding Effectiveness of Various Materials at a frequency range of 30MHz to 1GHz

The general trend for all tested materials was that shielding effectiveness increased with frequency.

Discussion

Based on the simulation results, the combination of Neodymium magnets and Chromium Rubber would give the highest shielding effectiveness as a hybrid gasket, while Trans-polyacetylene and Mu-metal may be able to cover a wider range of frequencies for a greater shielding effectiveness. Though trans-polyacetylene and chromium rubber were unable to be tested in physical experimentation, the simulations also set a precedent for Mu-metal to be more effective at lower frequencies and Neodymium magnets to have a high shielding effectiveness as a gasket.

From the actual physical measurements, the shielding effectiveness of the Mu-metal panel in use with FSG or neodymium magnets were similar to its shielding effectiveness when it was taped on to the aperture using aluminium tape, which was taken to be our control set-up. Since aluminium tape has proven to be an effective sealant with a high shielding effectiveness, this proves that gaskets can also be used in place of aluminium tape to prevent leakages. Neodymium gaskets may be used in future construction of commercial Faraday boxes as an easy open-and-shut sealant, as a complement to the Copper and Mu-metal materials that had the highest shielding effectiveness for high and low frequencies respectively.

Contrary to expectations, the addition of the FSG and neodymium magnets individually to the panel, showed similar results, with the shielding effectiveness of the neodymium magnets being slightly higher than FSG. This may be due to the lack of a strong compressive force acting on the FSG in our set up which fails to fully compress it, resulting in a lower shielding effectiveness than expected. It was also unexpected that the copper and aluminium sheets had a very similar shielding effectiveness across all frequencies, though this may be attributed to the thin panels that were used in testing. Thicker panels could be used in future experiments to observe a clearer distinction in shielding effectiveness between the two metals.

When comparing the simulations and actual physical measurements(only the frequency range of 300 MHz - 1.0 GHz will be considered), the shielding effectiveness of Mu-metal was higher in simulations than in actual measurements, despite a thicker sheet being used. This could be due to the perfect vacuum conditions of the simulations and the lack of deformities or kinks in the Mu-metal panel being used in the simulation causing this discrepancy, but it was much lower than the other conductive polymers in the simulation, which would be expected to have a lower shielding effectiveness than copper and aluminium. This could be due to certain mechanical property inaccuracies in the specifications of Mu-metal in the simulation software, where the material type was assumed to be Normal (dielectric) instead of a Lossy Metal.

Furthermore, the combination of neodymium magnets and FSG showed a lower shielding effectiveness of 19.8735dB as compared to the individual shielding effectiveness of neodymium magnets and FSG in the physical experimentation of 30.51 dB and 28.30dB respectively. This could be due to the lack of compression on the gaskets in the CST simulation. The ideal compression percentage of rubber gaskets is 40%, which was also not simulated in CST. [8] Hence, the shielding effectiveness of the gaskets in simulations may be lower than their actual shielding effectiveness.

In future experiments, more research could be done on conductive polymers and synthesising a suitable material for EMI shielding purposes, as well as the use of strong magnetic gaskets to provide a high shielding effectiveness while not compromising on a Faraday Box's ease of use.

Acknowledgements
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References

[1] Pan, C., Gaur, A. P. S., Lynn, M., Olson, M. P., Ouyang, G., & Cui, J. (2022, January 1). *Enhanced electrical conductivity in graphene–copper multilayer composite*. AIP Publishing.

[2] *Electrical conductivity: Copper vs aluminium cable*. Tai Sin Electric Limited. (2022, April 1).

[3] Avinash, Rai, M., & Yadav, R. K. (2014, November). *Characterization of shielding effectiveness of general metallized structure*. MECS Press.

[4] Bachir, G., Abdechafik, H., & Mecheri, K. (2016, September 6). *Comparison electromagnetic shielding effectiveness between single layer and multilayer shields*. IEEE Xplore.

[5] Brull, C. (2014, December 5). *Characterization of EMI shielding gaskets up to 40 GHz*. Interference Technology.

[6] East Coast Shielding. (2016). The importance of Gasket Junction design. The Importance of Gasket and EMI / RFI shields Junction Design.

[7] Tugirumubano, A., Vijay, S. J., Go, S. H., Ku Kwac, L., & Gun Kim, H. (2017, November 21). *Characterization of electromagnetic interference shielding composed of carbon fibers reinforced plastics and metal wire mesh based composites*. Journal of Materials Research and Technology.

[8] Melito, S. (2021, November 24). *Gasket compression explained: Rubber Gaskets*. Elastoproxy.