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# EMI Shielding Performance of Thin and Thick Graphene Films Placed Within Integrated Power Modules

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# TOPICS OUTLINE

1. Shielding effectiveness
2. Key Drivers for EMI Shielding Technology Advancements

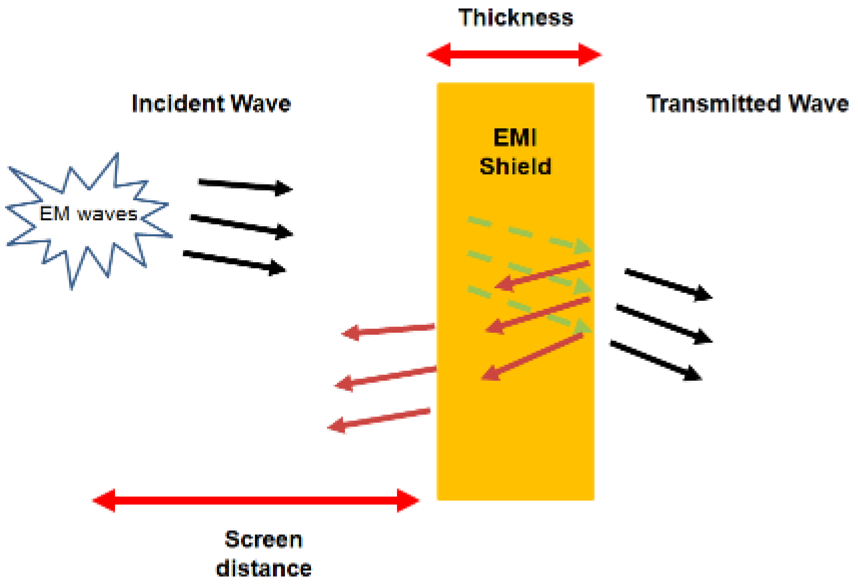
3. EMI Shielding Strategy Against Magnetic Field Sources

4. EMI Shield Inside Electronic Package

5. Comparison between thin and thick films

6. Final Recommendations

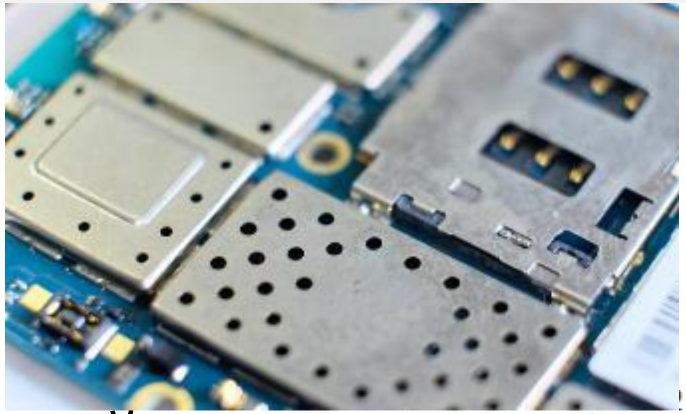
# SHIELDING EFFECTIVENESS OF A SINGLE LAYER




Shielding Effectiveness (SE) is used to describe a material's effectiveness in shielding against electromagnetic (EM) waves. It essentially quantified the drop in amplitude of an incident wave after propagating through the shielding material. SEs are classified as far-field and near-field distances based on the screen's distance from the source

[1]https://resources.altium.com/p/emi-reducing-pcb-shielding-techniques-incorporate-your-designs
[2] https://www.harwin.com/blog/emc-emi-shielding-explained/

- **Using Electric Fields [ Electric Dipole excitations]**
- $SE = 20\log_{10}\left|\frac{E_i}{E_t}\right|$
- SE: Shielding effectiveness
- $E_i$: Incident electric field
- $E_t$:Transmitted electric field
- **Using Magnetic Fields (Loop antenna excitation)**
- $SE = 20\log_{10}\left|\frac{H_i}{H_t}\right|$
- $H_i$: Incident magnetic field
- $H_t$:Transmitted magnetic field
- **Plane Wave or Far Field Illumination:**
- $SE = 20\log_{10}\left|\frac{F_i}{F_t}\right|$
- $F_i$: E or H field intensity of the incident field
- $F$: E or H field intesity of the transmitted field



# ANALYTICAL MODEL FOR COMPUTING THE SHIELDING EFFECTIVENESS OF A SINGLE LAYER

$A = 131.4t\sqrt{f\mu_r\sigma_r}$ (approximate value) [1-2]

RL (plane wave) $= 168 + 10\log\frac{\sigma_r}{\mu_r f}$ (approximate value) [1-2]

RL (electric dipole) $= 332 + 10\log\frac{\sigma_r}{\mu_r f^3 d^2}$ (approximate value) [1-2]

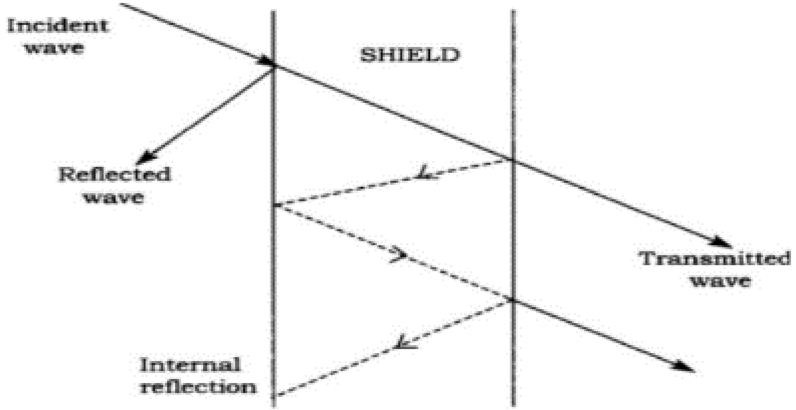
RL (magnetic dipole) $= 14.6 + 10\log\frac{\sigma_r f d^2}{\mu_r}$ (approximate value) [1-2]

$SE = A + R$

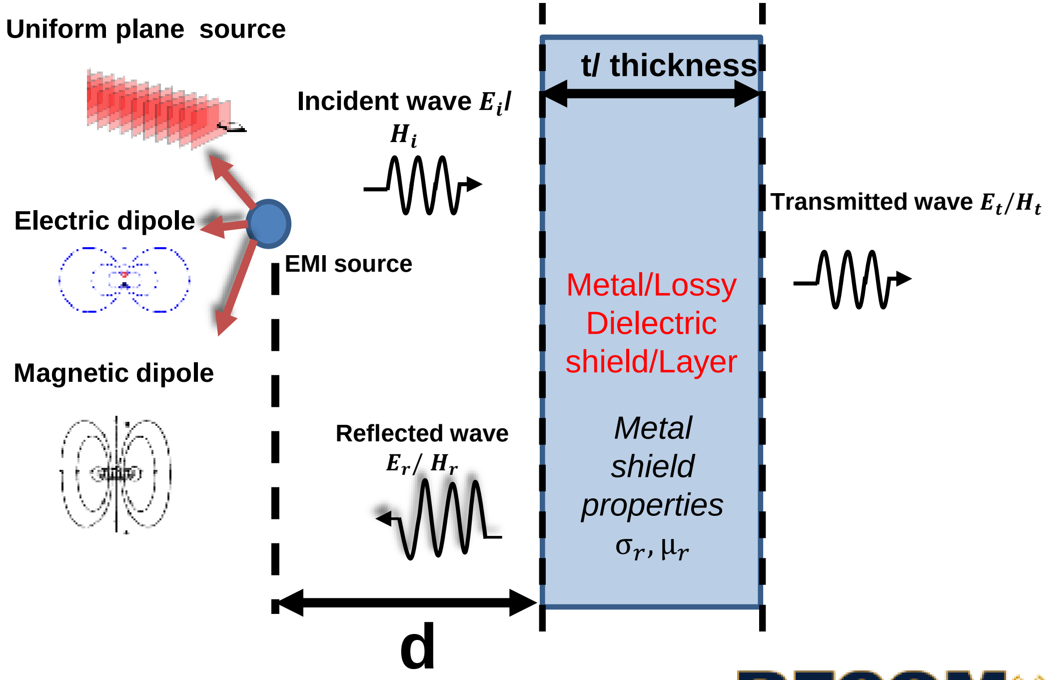
A: absorption loss in dB
RL: reflection loss in dB
$\mu_r$: Relative magnetic permeability
$\sigma_r$ : Electrical conductivity with respect to Copper
t: Thickness of the shield in m
d: screen distance in m

**Shielding effectiveness is the difference between incident and transmitted waves**

**Equations have some crude assumptions, especially regarding wave impedance estimation in the near field.**




An illumination of shielding effectiveness for metal/barrier




An EM screen model


[3]H. W. Ott, Electromagnetic Compatibility Engineering, Hoboken, NJ, USA:Wiley, 2009.
[4] Paul,C.R.(2006). Introduction to electromagnetic compatibility .Hoboken, NJ:Wiley.
[5] Geetha, S., Satheesh Kumar, K. K., Rao, C. R., Vijayan, M., & Trivedi, D. C. (2009). EMI shielding: Methods and materials—A review. *Journal of applied polymer science*, *112*(4), 2073-2086.

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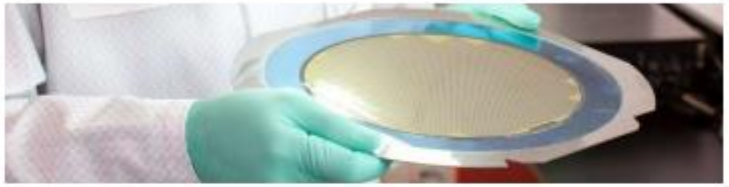
# KEY DRIVERS FOR EMI SHIELDING TECHNOLOGY ADVANCEMENTS



1. Higher-density semiconductor packaging structures

2.Increasing electromagnetic pollution

3.Era of Internet of Things (IoT)

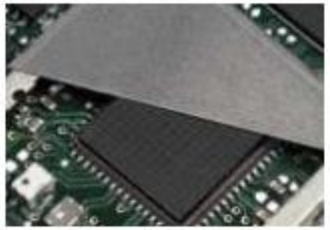
4. Compliance with tightening EMC regulations

Where is it required?

1. Tightly packed highly sensitive components
2. Constant move toward miniaturization
3. Growing wireless technology applications

EMI shielding is applicable to various components.

- System-in-Package (SiP)
- System-on-Chip (SoC)
- Microcontrollers (MCU)
- Application processors
- Power amplifiers
- Wireless modules (Wi-Fi, Bluetooth)
- Radio Frequency (RF) modules
- Memory
- Sensors
- Digital Signal Processors (DSP)
- Application-specific integrated circuits (ASIC)
- Field-programmable gate arrays (FPGA)
- Analog-Digital Converters (ADC)



[6]Ko Odreitz, ELECTROMAGNETIC COMPATIBILITY ESSENTIALS ,June 2021
[10]https://dm.henkeldam.com/is/content/henkel/loctite_package_level_emi_shielding_solutions_brochure__1_



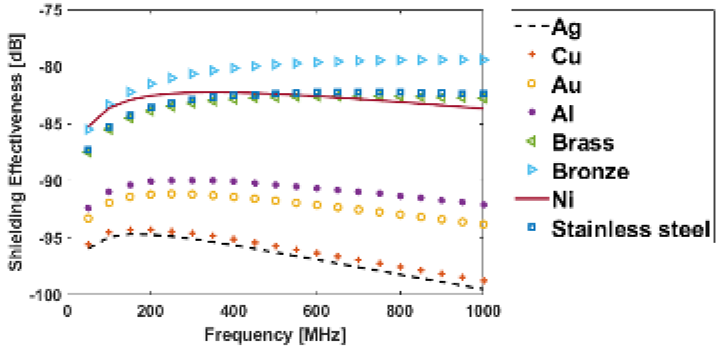
RFCOM Lab
RF Communications & Terahertz Lab

# Analytical Model Predictions for Single Layer-5µm Thickness

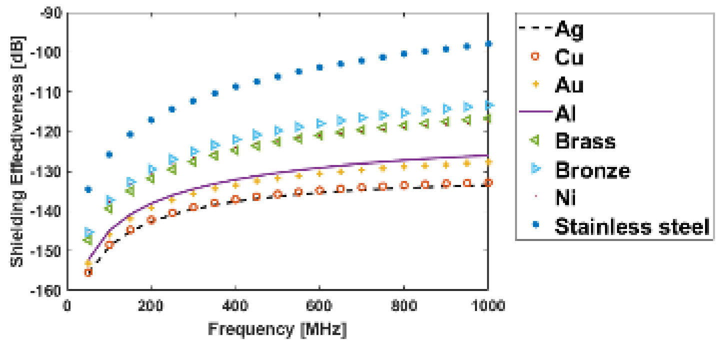
Shielding effectiveness of infinite planes with different planes and thicknesses are analyzed;

Best conductors such as Ag and Cu are found to be the most effective.
Magnetic materials did not show higher shielding effectiveness in certain configurations and frequencies even for magnetic dipole sources.

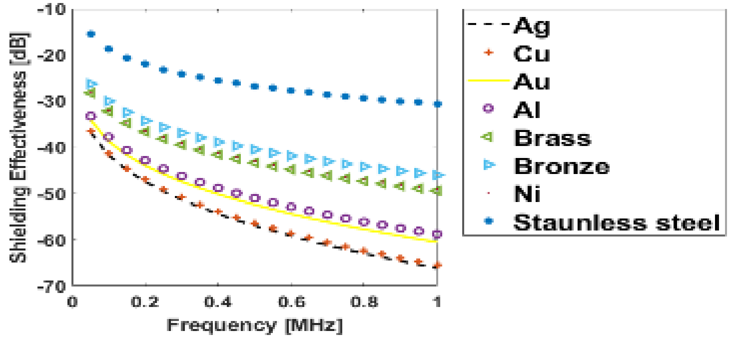
## Uniform Plane source



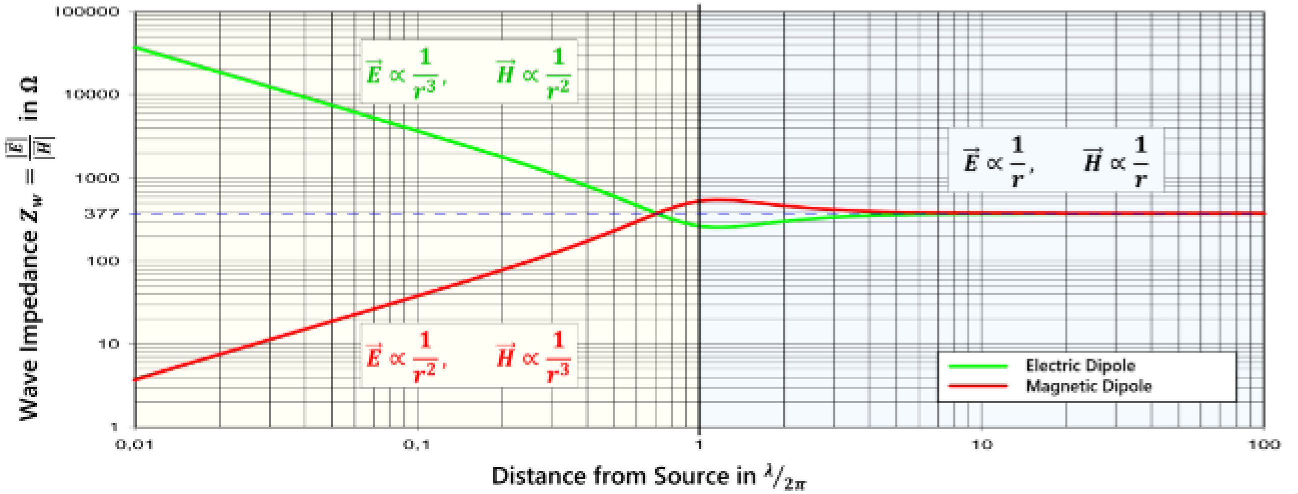

## Electric dipole source




## Magnetic dipole source



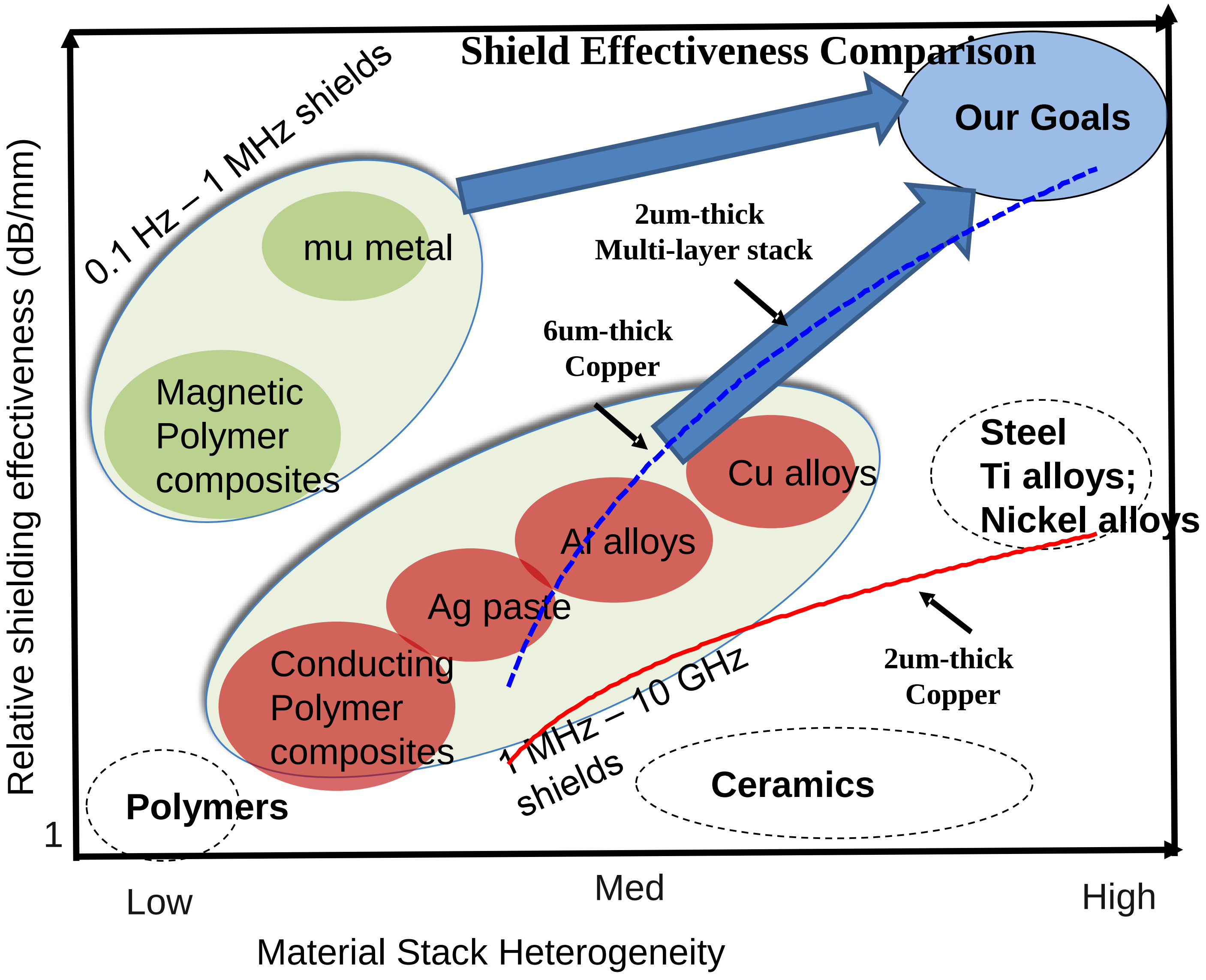

| Shield metals | Relative permeability ($\mu_r$) | Relative conductivity with respect to Copper ($\sigma_r$) |
|---|---|---|
| Silver | 1 | 1.05 |
| Copper | 1 | 1 |
| Gold | 1 | 0.7 |
| Aluminum | 1 | 0.61 |
| Brass | 1 | 0.26 |
| Bronze | 1 | 0.18 |
| Nickel | 600 | 0.25 |
| Stainless steel | 500 | 0.02 |




In terms of shielding effectiveness, highly-conductive metals such as Cu and Ag are most effective;
Shielding performance with magnetic field sources is lower compared to electric dipole sources and plane wave sources ( Far-field).
Single layer EM shield of Cu and Ag show good performance against electric field and plane wave sources in terms of SE.

[6]Ko Odreitz, ELECTROMAGNETIC COMPATIBILITY ESSENTIALS ,June 2021

# RESEARCH OBJECTIVES



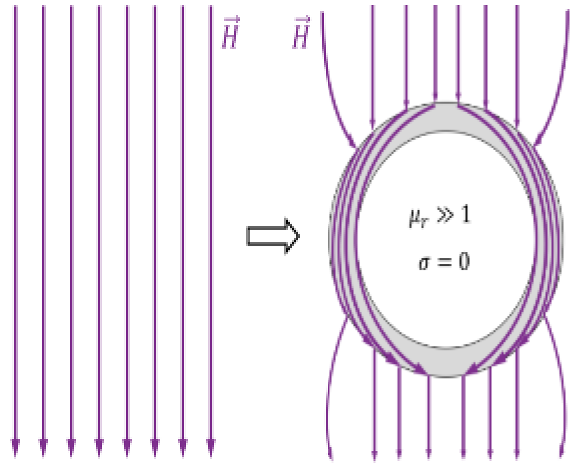

- Commercial SE materials are 10-30 dB
- SE against the magnetic field is more complicated
- Applications such as electric vehicles, military, and medical sensors are more stringent to SE requirements compared to traditional electromagnetic regulations such as FCC, CE, CCC, CVI, etc.

Targets

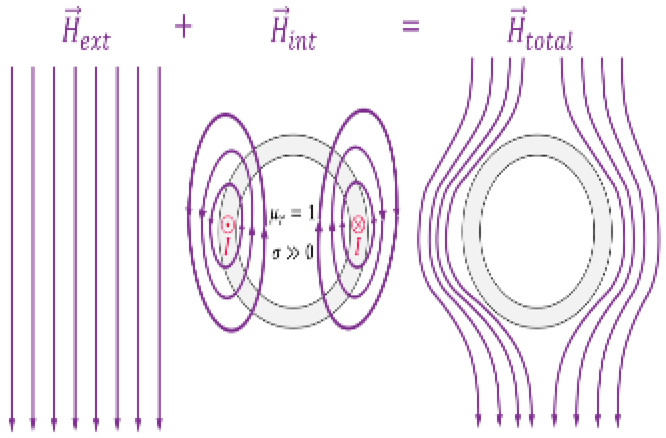
- ❑ Materials that have SE better than 30 dB at low frequencies.
- ❑ EMI shield as metal Can and barriers between components at PCB and system level

# EMI SHIELDING STRATEGY AGAINST MAGNETIC FIELD SOURCES

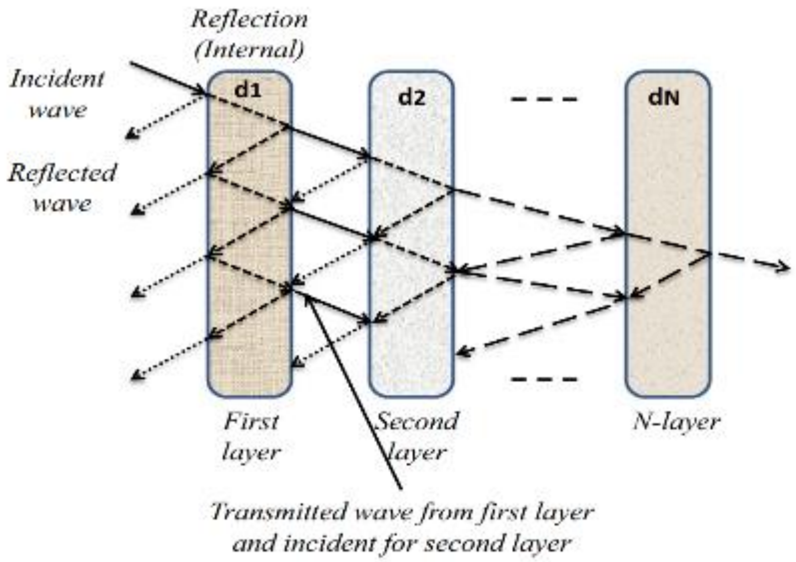
## 1 Low-frequency H-fields by permeability




## 2 High-frequency H-fields by induced currents




## 3 Principle of multi-reflection in a multilayered structure




The bottom line

- Shielding by high permeability traps the magnetic field lines inside the shielding material.
- Shielding by induced currents squeezes the magnetic field lines out of the protected area.

The primary shielding mechanism for such thin multilayered shields is multiple reflections caused by impedance mismatch at the interfaces between the magnetic and conductive thin layers. Furthermore, employing copper as a conductive material produces higher absorption loss, which contributes to higher total shielding effectiveness

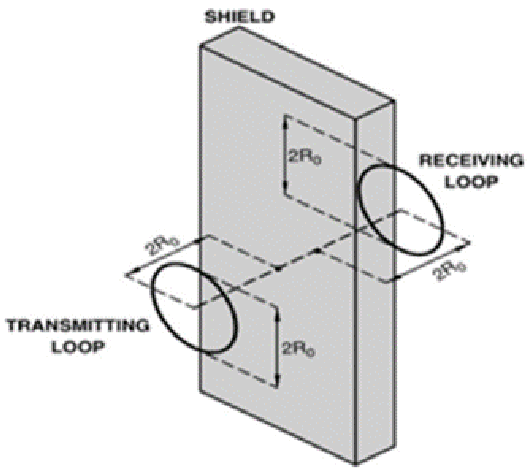

[6] Ko Odreitz, ELECTROMAGNETIC COMPATIBILITY ESSENTIALS ,June 2021
[7]Gaoui, Bachir & Hadjadj, Abdechafik & Kious, Mecheri. (2017). Enhancement of the shielding effectiveness of multilayer materials by gradient thickness in the stacked layers. Journal of Materials Science: Materials in Electronics. 28. 1-8. 10.1007/s10854-017-6920-8.

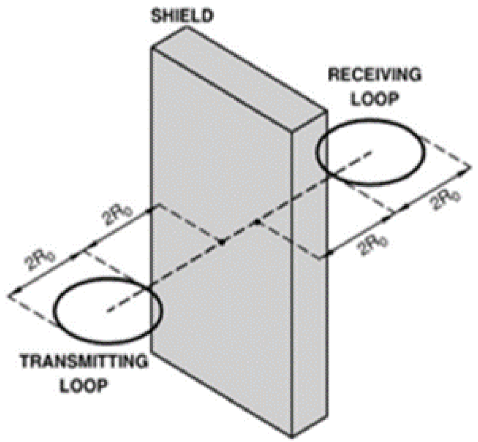
# SHIELDING ANALYSIS OF HIGH-CONDUCTIVITY THIN FILMS OF GRAPHENE-LAYER LEVEL

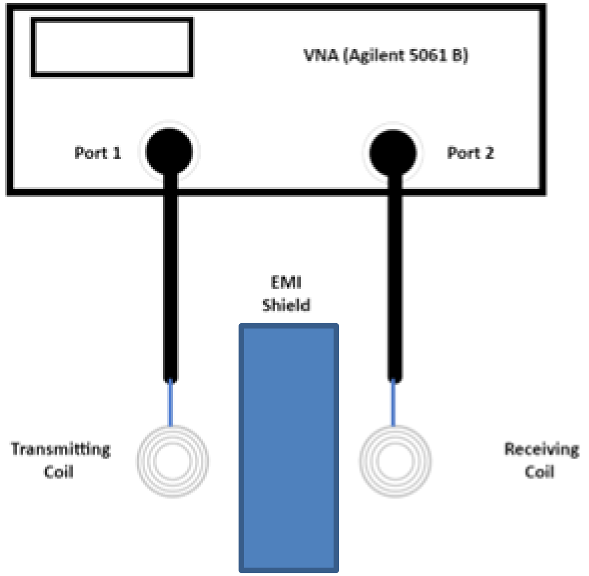
| Proposed material | Electrical conductivity (S/m) | Electrical conductivity with respect to copper ($\sigma_r$) | Thermal conductivity (W/m.K) |
|---|---|---|---|
| Copper (Cu) | $58 \times 10^6$ | 1 | 400 |
| Graphene_Sample#1 | $21 \times 10^4$ | 0.003 | 3000 |
| Graphene_Sample#2 | $1 \times 10^6$ | 0.02 | 4000 |
| Graphene_Sample#3 | $29 \times 10^6$ | 0.5 | 4000 |
| Graphene_Sample#4 | $46.4 \times 10^6$ | 0.8 | 4000 |
| Nickel (Ni) | $14.5 \times 10^6$ | 0.25 | 90 |

SE is determined by the difference between the transmission coefficient $S_{21}$ in the presence and absence of the EMI suppression modeling. Notably, the SE is broken down into two main components: absorption and reflection losses. Based on the above, the shielding effectiveness is given by

$$SE = S_{21}\,(w/o\ shield) - S_{21}(\,with\ shield) \quad (1)$$

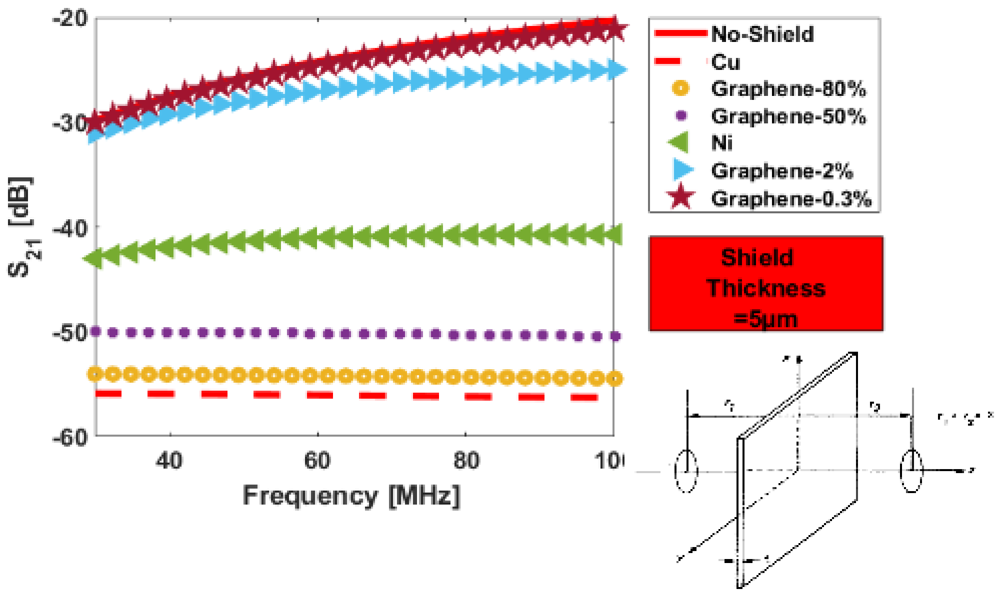


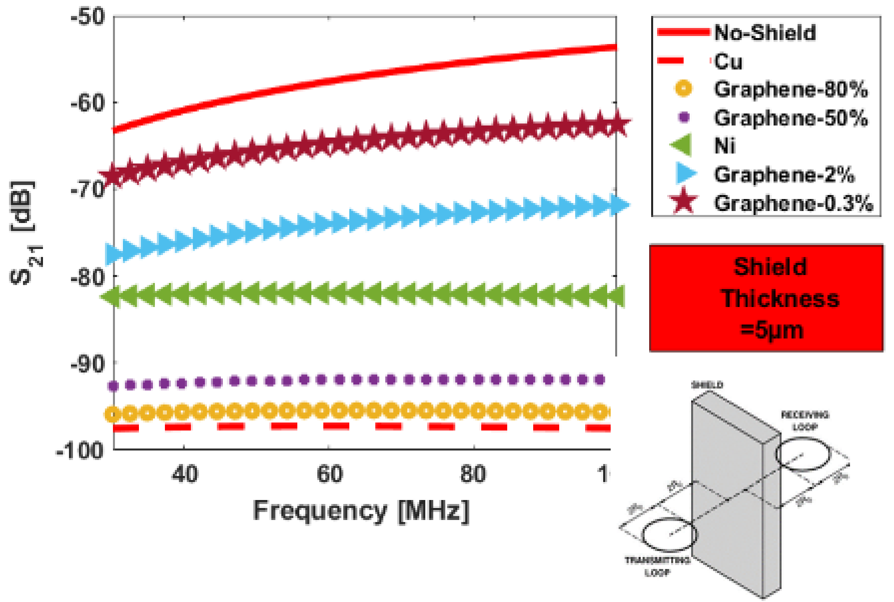

[8]S. Celozzi, R. Araneo and G. Lovat, Electromagnetic Shielding, Hoboken, NJ, USA:Wiley, 2008

# SHIELDING EFFECTIVENESS - MATERIALS COMPARISON




[a] NSA 65-6

| Material | SE (dB) |
|---|---|
| Sample #1 | 2 |
| Sample #2 | 5 |
| Sample #3 | 20-30 |
| Sample #4 | 24-34 |
| Cu | 25-36 |
| Ni | 13-20 |




[b] IEEE 299

| Material | SE (dB) |
|---|---|
| Sample #1 | 10 |
| Sample #2 | 17 |
| Sample #3 | 29-38 |
| Sample #4 | 33-41 |
| Cu | 34-43 |
| Ni | 19-28 |

According to the NSA 65-6 and IEEE- 299 standards, Graphene samples with $\sigma_r$= 0.8 exhibits performance as good as Cu in the frequency range of 30-100MHz

SE of the materials based on the IEEE -299 standards show higher values compared to the NSA 65-6


[8]S. Celozzi, R. Araneo and G. Lovat, Electromagnetic Shielding, Hoboken, NJ, USA:Wiley, 2008

[9]P. R. Bannister, "New Theoretical Expressions for Predicting Shielding Effectiveness for the Plane Shield Case," in IEEE Transactions on Electromagnetic Compatibility, vol. EMC-10, no. 1, pp. 2-7, March 1968, doi: 10.1109/TEMC.1968.302900.

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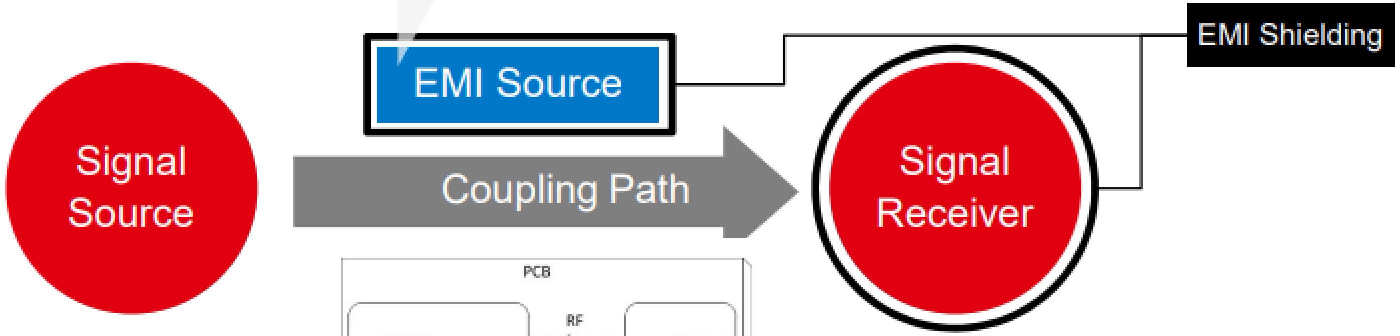
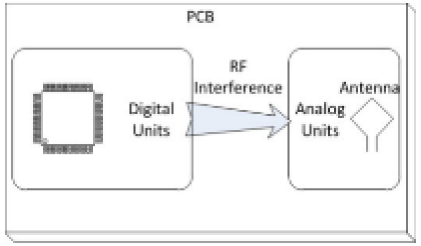
# ELECTROMAGNETIC INTERFERENCE AND COMPATIBILITY [ EMI / EMC]

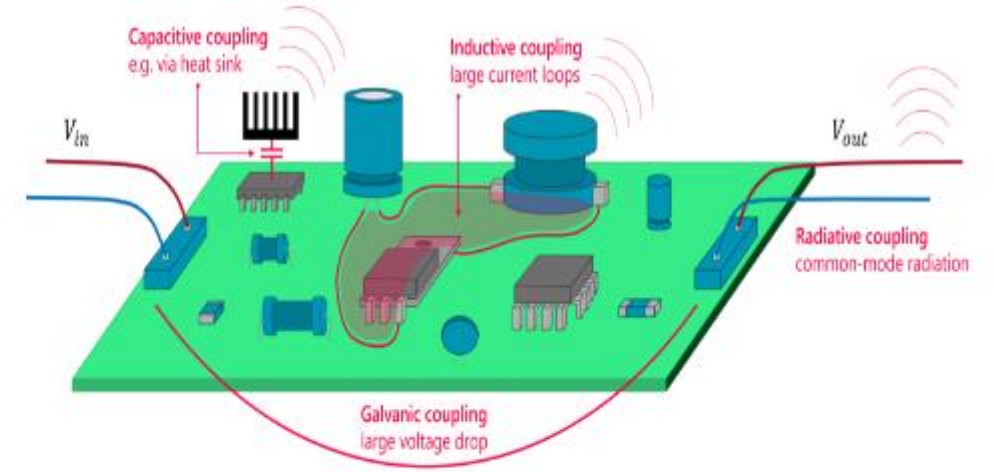
Electromagnetic compatibility' means the ability of equipment to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to other equipment in that environment.

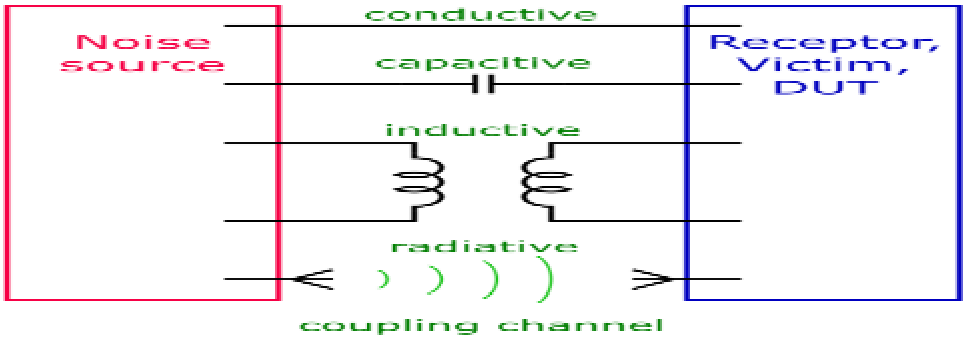
General definition

1. The system does not interfere with other systems (emission)
2. The system is not susceptible to emissions from other systems (immunity)
3. The system does not interfere with itself (signal integrity).




Noise source: There are numerous sources of electromagnetic interference

Coupling path: The interfering signal must enter our system through some path.

- Galvanic coupling (conductive through a common impedance)
- Capacitive coupling (near-field)
- Inductive coupling (near-field)
- Radiated coupling (far-field)

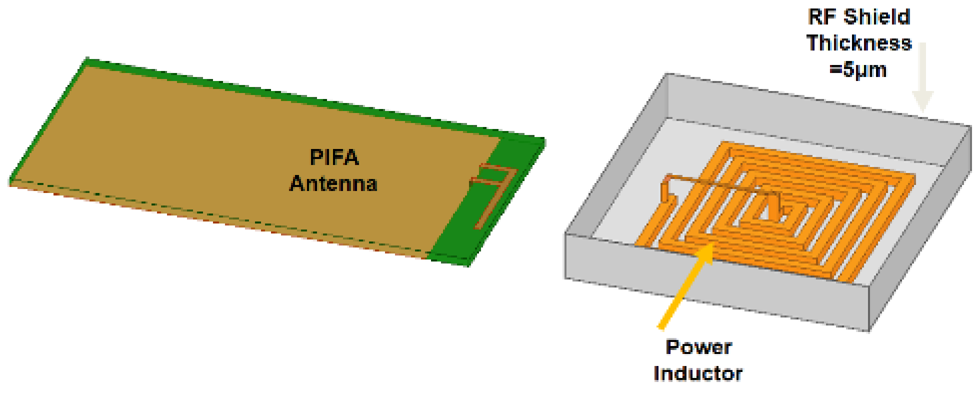
Receptor: This is the system we need to protect. An EMC test technician would call this system a DUT (device under test).

- Especially analog parts of any electronic system, e.g. operational amplifiers or analog/digital converters, are susceptible to EMI.

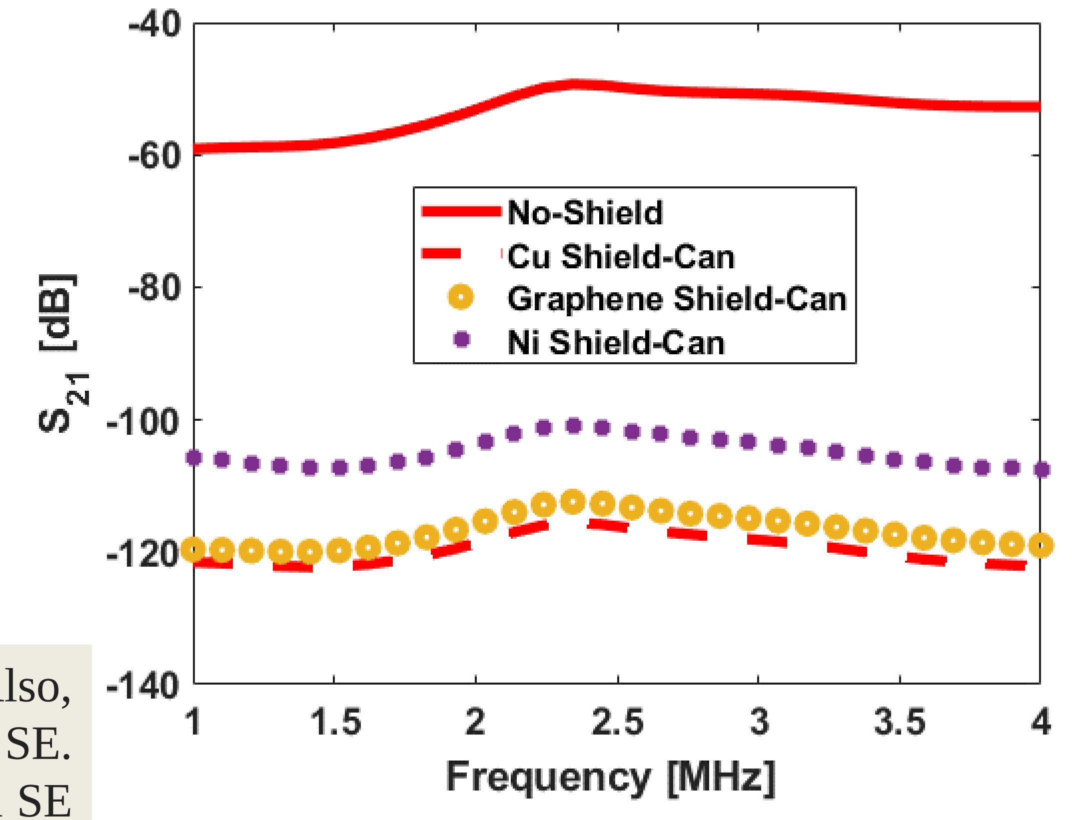
**EMI shields are used as an advanced option to meet the EMC regulations and mitigate all EMI couplings**


[6]Ko Odreitz, ELECTROMAGNETIC COMPATIBILITY ESSENTIALS ,June 2021
[10]https://dm.henkeldam.com/is/content/henkel/loctite_package_level_emi_shielding_solutions_brochure__1_

# SCENARIO#1: COUPLING SET UP BETWEEN A PIFA ANTENNA AND A POWER INDUCTOR - SYSTEM LEVEL



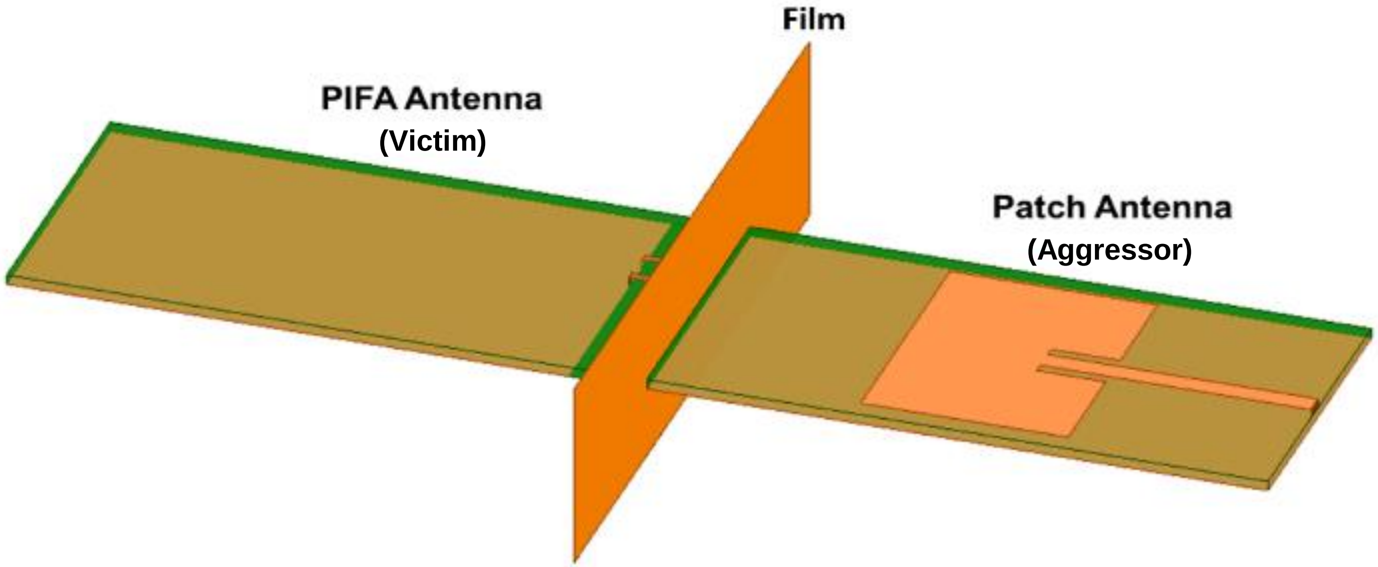

Scenario#1 represents the electromagnetic (EM) coupling between a power inductor ( aggressor) and a PIFA antenna ( victim) with and without an RF shield.

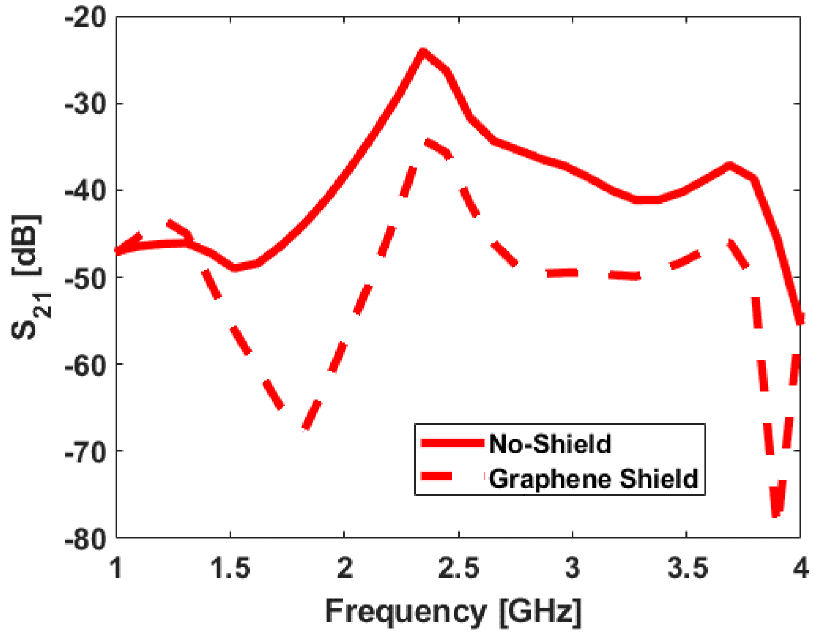



A graphene film of the thickness of 5 µm and $\boldsymbol{\sigma_r}$ = 0.8 was used. Also, Ni and Cu films of the same thickness were used to evaluate their SE. Notably, graphene shielding showed a fair performance improvement in SE between the power inductor and the PIFA antenna. It was as much as 60 dB across 1- 4 GHz. Commercial Ni shows only SE = 40 dB. Cu performs slightly better with only an additional 1-2 dB as compared to graphene films.

Fully and semi-shielded power inductors for power discrete inductors and on-die chip inductors are used to reduce the undesired magnetic radiation of the inductor

# SCENARIO#2: COUPLING SET-UP BETWEEN THE PIFA ANTENNA AND A PATCH ANTENNA - SYSTEM LEVEL




Scenario#2

This scenario refers to an antenna radiating onto IC chips such as the aggressor IC. In this case, graphene films are used as an EMI shield between the PIFA and the patch antennas to enhance isolation between electronic components.

EMI shield as a barrier/ wall between components is used to reduce the coupling between components in the PCB and package level.

As noted, Scenario#2 represents the coupling of a patch antenna to a PIFA antenna operating at 2.4 GHz. The EM shielding of graphene with $\boldsymbol{\sigma_r}$ = 0.8 has an SE value of 10 dB at 2.4 GHz and of 20-30 dB across the same frequency band

# BENCHMARK EMI SHIELDING WITH CURRENT APPROACHES

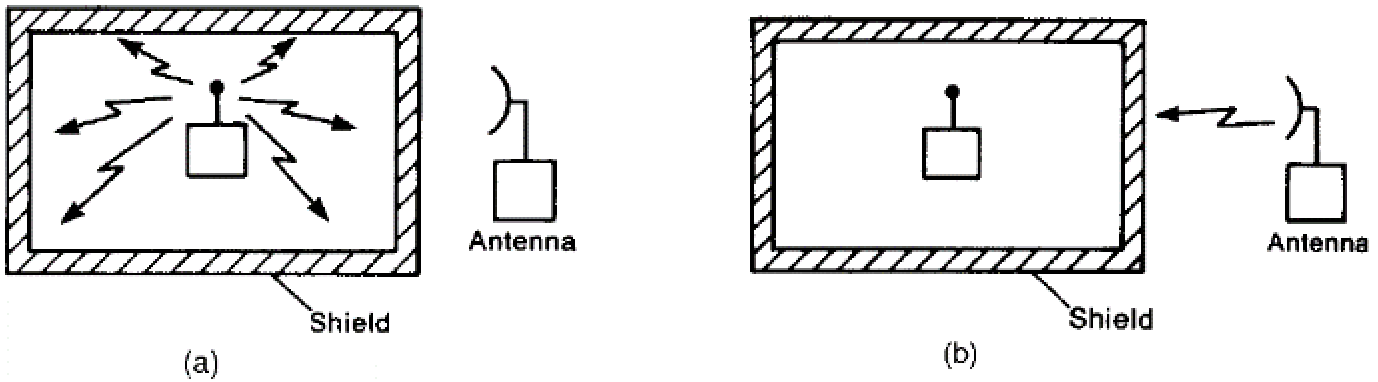
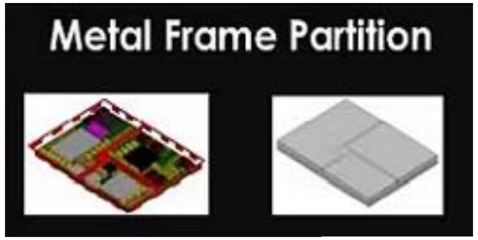
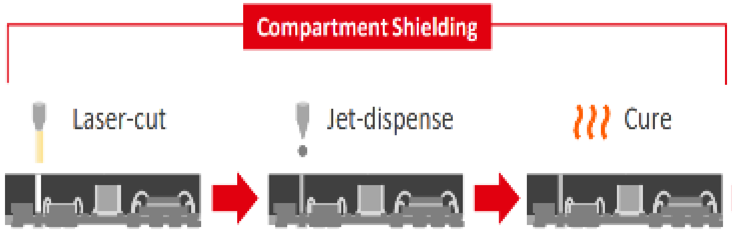


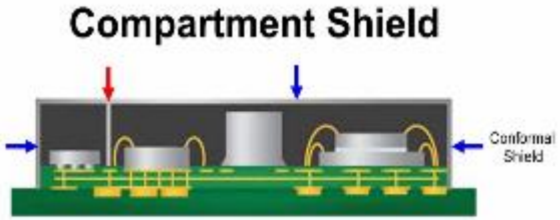

Illustration of the use of a shielded enclosure: (a) to contain radiated emissions and (b) to exclude radiated emissions

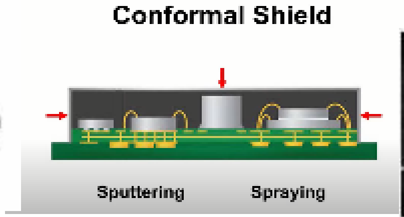
| Metal can shields | Sputtered metal on packages | Sprayed metal on packages | Plated metal via arrays and walls |
|---|---|---|---|

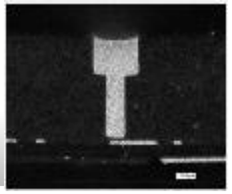






**Some techniques intend to shield the victim rather than the source, especially for the far-field shielding**

**There are two types of EMI shields:**

1. **Conformal – Thick films**
2. **Compartment- Thin films**

**Thick films – Coating and spraying**
**Thin films- PVD**

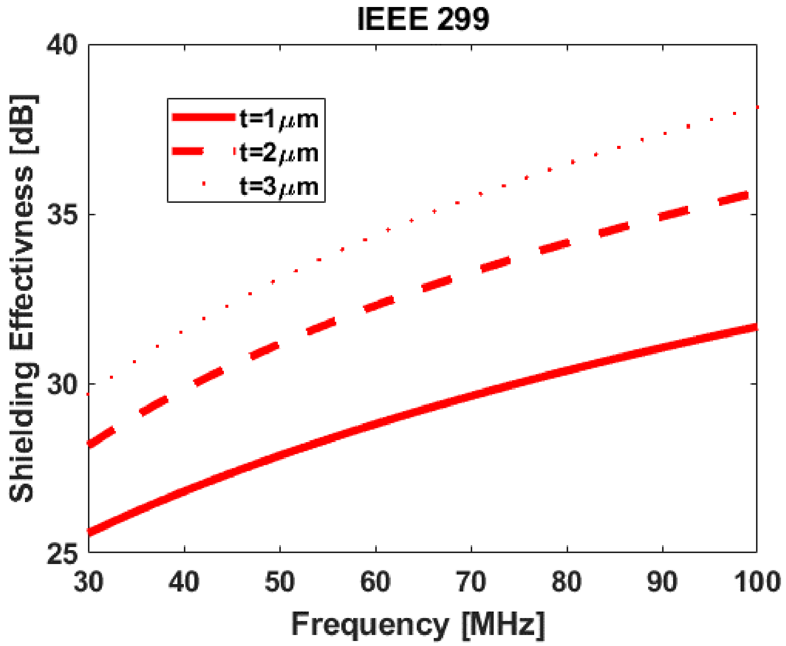
***Where is the value proposition:***

- ***Higher shielding effectiveness***
- ***Easier process integration***

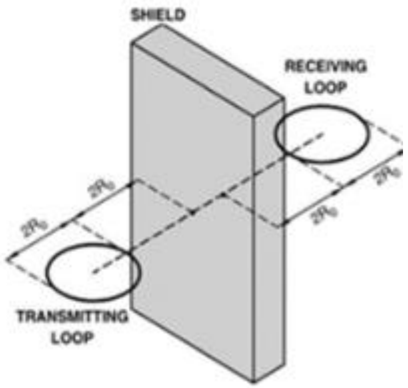
Study the thickness of the layers versus the electrical conductivity

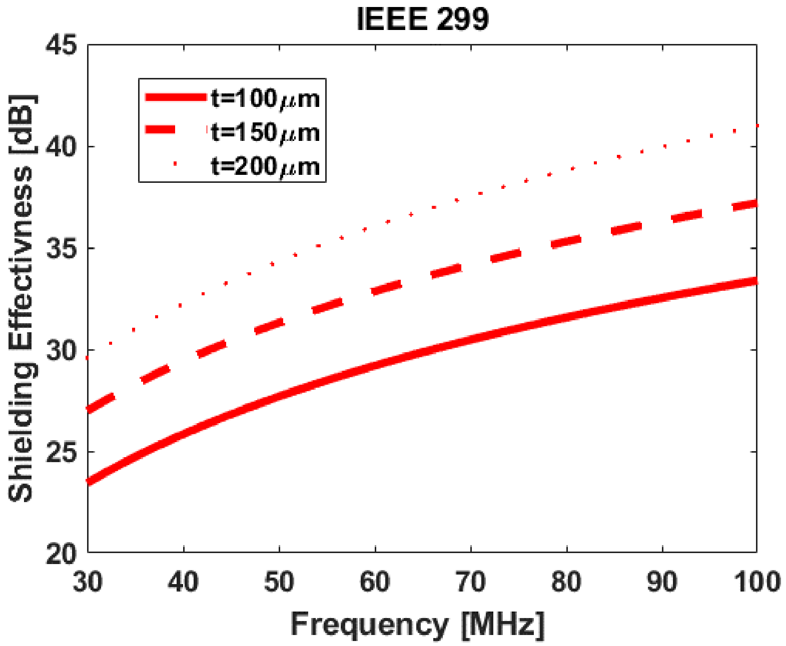

[10]https://dm.henkeldam.com/is/content/henkel/loctite_package_level_emi_shielding_solutions_brochure__1_
[4] Paul,C.R.(2006). Introduction to electromagnetic compatibility .Hoboken, NJ:Wiley.

# COMPARISON BETWEEN THICK AND THIN FILMS- IEEE 299




[a]




[b]

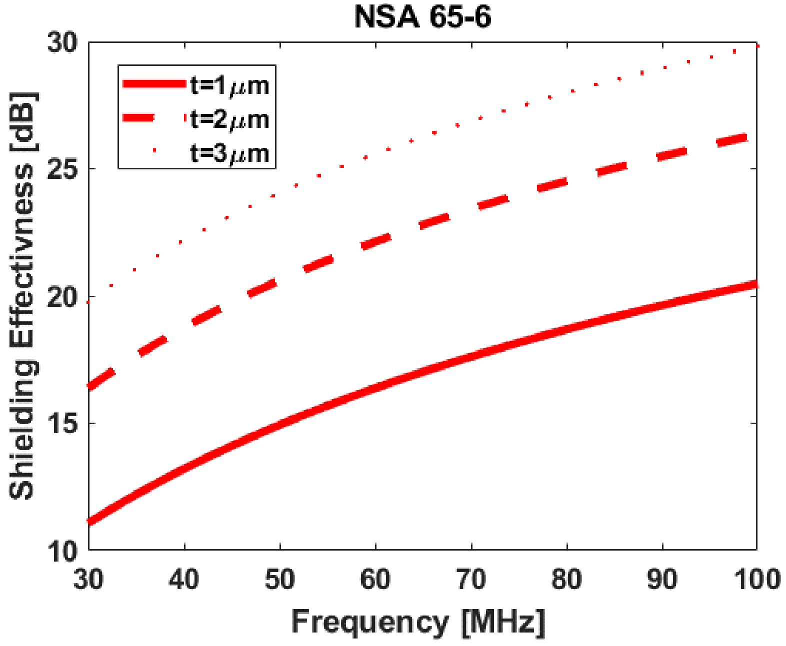
SE for thin (1-3 μm) [a] and thick (100-200 μm) [b] graphene films based on the IEEE 299 standard using a magnetic field source/ generator

| | **Graphene Sample#4** ($\sigma = 46.6 \times 10^6$ **S/m**) | | | **Graphene Sample#2** ($\sigma = 1 \times 10^6$ **S/m**) | | |
|---|---|---|---|---|---|---|
| **Thickness in μm** | 1 | 2 | 3 | 100 | 150 | 200 |
| **SE in dB** | 25-32 | 26-36 | 30-38 | 22-33 | 27-37 | 30-41 |

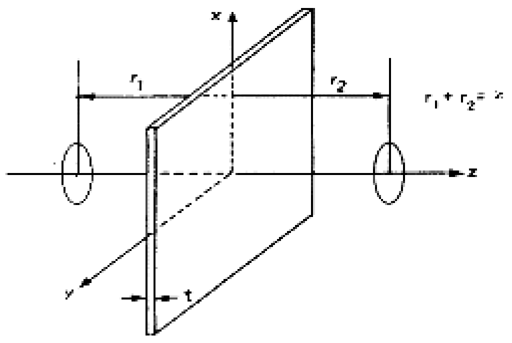
Thinner EMI shield of graphene samples of higher electrical conductivity ($\sigma = 46.6 \times 10^6$ S/m) exhibits the good performance as EMI shield of thick graphene samples of low electrical conductivity ($\sigma = 1 \times 10^6$ S/m) based on the IEEE -299 standard

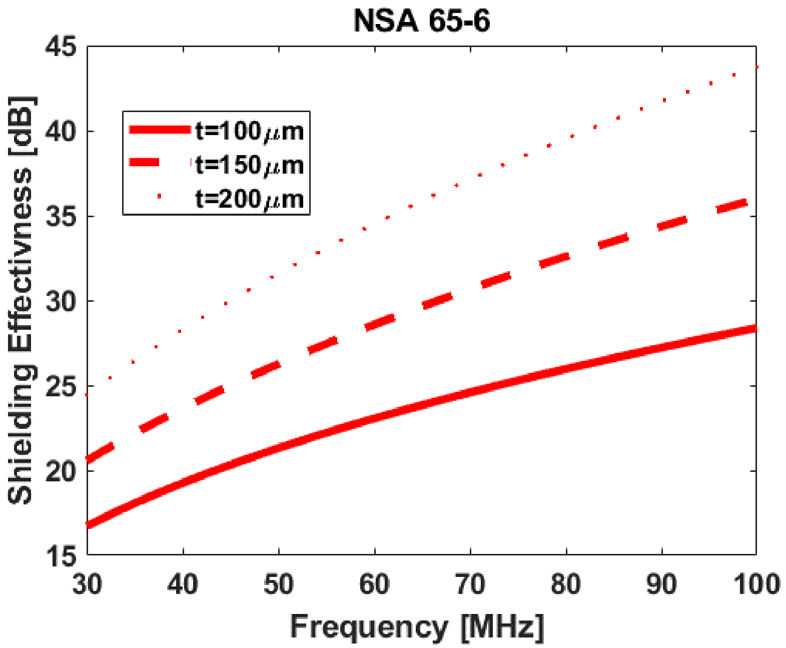
[8]S. Celozzi, R. Araneo and G. Lovat, Electromagnetic Shielding, Hoboken, NJ, USA:Wiley, 2008

# COMPARISON BETWEEN THICK AND THIN FILMS- NSA 65-6




[a]




[b]

SE for thin (1-3 μm) [a] and thick (100-200 μm) [b] graphene films based on the NSA 65-6 standard due to a magnetic field source/generator.

| | Graphene Sample#4 ($\sigma = 46.6 \times 10^6$ S/m) | | | Graphene Sample#2 ($\sigma = 1 \times 10^6$ S/m) | | |
|---|---|---|---|---|---|---|
| **Thickness in μm** | 1 | 2 | 3 | 100 | 150 | 200 |
| **SE in dB** | 11-16 | 16-26 | 20-30 | 17-28 | 21-36 | 25-44 |

Thinner EMI shield of graphene samples of higher electrical conductivity ($\sigma = 46.6 \times 10^6$ S/m) exhibits slightly less performance compared to EMI shield of thick graphene samples of low electrical conductivity ($\sigma = 1 \times 10^6$ S/m) based on the NSA 65-6 standard

[9]P. R. Bannister, "New Theoretical Expressions for Predicting Shielding Effectiveness for the Plane Shield Case," in IEEE Transactions on Electromagnetic Compatibility, vol. EMC-10, no. 1, pp. 2-7, March 1968, doi: 10.1109/TEMC.1968.302900.

# CONCLUSION

| Material | Measurement / simulation set up | Frequency | SE (dB) | | Reference |
|---|---|---|---|---|---|
| Cu( 4μm) | Screen distance=0.5mm | 100 MHz | 40 (simulation) 30 (measurement) | | 11 |
| Ni( 5μm) | | 100 MHz | 25 (simulation) 18 (measurement) | | |
| Cu( 6μm) | | 100 MHz | 6 (simulation) | | 12 |
| Ni( 6μm) | | 100 MHz | 4 (simulation) | | |
| Cu( 5μm) | | 100 MHz | 27 (measurement) | | 13 |
| Graphene+ PET substrate (4.26μm+300μm ) σ=262 S/m | | 1-10 GHz | 22-46 ( measurement) | | 14 |
| | | | NSA 65-6 | IEEE 299 | |
| Graphene sample #1 ( 5μm) | Screen distance= 2mm | 30-100MHz | 2 (simulation) | 10 (simulation) | This work |
| Graphene sample #2 ( 5μm) | | | 5 (simulation) | 17 (simulation) | |
| Graphene sample #3 ( 5μm) | | | 20-30 (simulation) | 29-38 (simulation) | |
| Graphene sample #4 ( 5μm) | | | 24-34 (simulation) | 33-41 (simulation) | |

[11]C. Chen, Y. Tseng, T. Wu, I. Lin, C. Fu and K. Liao, "Prediction of near-field shielding effectiveness for conformal-shielded SiP and measurement with magnetic probe," 2015 IEEE 24th Electrical Performance of Electronic Packaging and Systems (EPEPS), 2015, pp. 77-80, doi: 10.1109/EPEPS.2015.7347133

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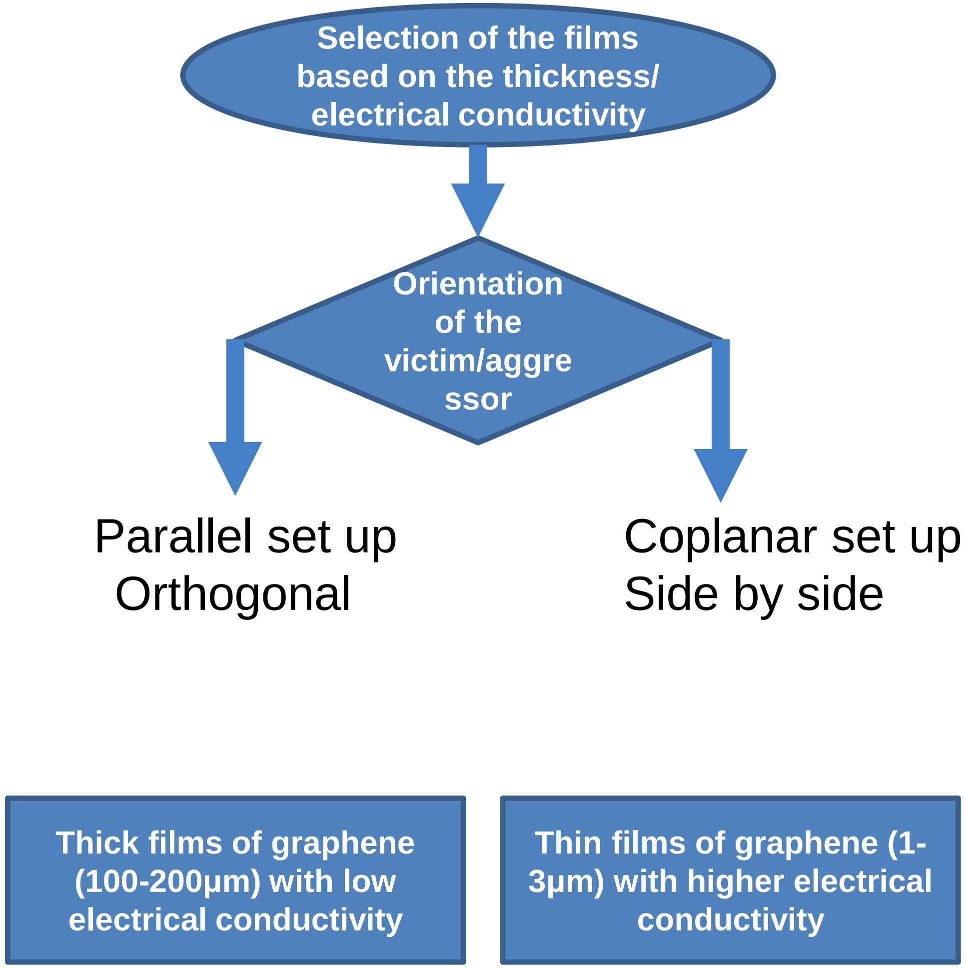
[13] Tai, M. F., Kok, S. L., Mukai, K., Hotz, S., Brooks, P., & Cocina, D. R. (2017). EMI Shielding Performance For Varies Frequency by Metal Plating on Mold Compound. Advances in Science, Technology and Engineering Systems Journal, 2(3), 1159–1164. https://doi.org/10.25046/aj0203146

[14] A.O.Watanabe, S.Jeong, S.Kim, Y.Kim, J.Min, D.Wong, M.R.Pulugurtha, R.Mullapudi, J.Kim and R.R Tummala,"Highly-Effective Integrated EMI Shields with Graphene and Nanomagnetic Multilayered Composites," 2016

# CONCLUSION

- Graphene films exhibit desirable features for EMI shielding including high conductivity, flexibility, and lighter weight.
- These films can be placed between power and RF circuits in electronic packages for shielding. If processed to achieve high electrical conductivity, graphene has superior shielding effectiveness and can potentially, in the future, replace commercial shielding materials such as Cu and Ni.
- Notably, the orientation of power and RF components within an electronic package can play a key role in SE designs
- A comparative materials study based on the NSA 65-6 standard showed that thicker graphene composite films perform better than thin graphene films
- Thick graphene films may be more attractive for shielding in 3D electronic packages and embedded chips.
- However, as noted, both thin and thick graphene films show similar performance in terms of SE based on the IEEE 299 standard.
- Thin graphene films can be used for EMI shielding in multi-chip modules (MCMs) and 2.5D electronic packages where higher density and smaller spacing between components are required



Thank you!

Q&A