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Abstract— **Engineering of absorbing materials for gaskets that would be used between two metal plates to reduce electromagnetic emissions and improve immunity of electronic equipment is considered. An analytical model of a composite based on the Maxwell Garnett formulation for multiphase mixtures, as well as the shielding effectiveness of this material, are presented. The full-wave numerical computational results for the structure consisting of two overlapping metal plates and an engineered gasket composite material in the place of the overlap are presented.**

Keywords-electromagnetic shielding effectiveness; dielectric base material; ferrite, ceramic, and carbon inclusions, Maxwell Garnett formulation

I. INTRODUCTION

Conductive or absorbing gaskets are frequently used in the gaps between the metal plates to reduce emissions, and improve the immunity of electronic equipment. Any slot in an enclosure constructed of highly-conductive materials, may play the part of an unintentional antenna, if surface current lines cross this slot. The problem is to eliminate slots as well as possible surface currents that are culprits of undesirable emission. Conductive gaskets are typically used between the conductive plates of an enclosure, for example, around door frames of an electronic block. However, conductive gaskets do not always ensure perfect electrical contact between the plates. This can lead to a discontinuity of surface currents, resulting in unwanted electromagnetic coupling and emissions.

The presence of a harsh environment may compromise the shielding integrity of a structure that relies on conductive gaskets to achieve low-loss electrical contact between the metal plates. Exposure to salt-fog or other chemicals can result in a significant decrease in shielding effectiveness capability for conductive gaskets, even when the conductive particles are embedded in a polymer such as fluorosilicone or EPDM rubber. Additionally, the use of conductive gaskets with metal enclosures can result in galvanic corrosion, if proper care is not applied in the selection of compatible materials. The shielding effectiveness can also be degraded by the presence of dirt, dust, grease, etc. between the gasket and one of the conductive enclosure surfaces. Substantial temperature and pressure variations could also deteriorate the mechanical and electrical quality of the contact between the conductive plates. A reasonable solution to this problem is the application of absorbing materials with specially engineered frequency characteristics for gaskets and shields.

The objective of this paper is to present an analytical model to solve at least two problems: (1) engineering a suitable material for a gasket that will substantially reduce radiation from the gap between two overlapping conductive plates in the given frequency range (within the microwave band), and (2) full-wave numerical modeling of the geometry that contains this gasket material.

II. MODEL OF A MATERIAL FOR A GASKET

A reasonable approach to the mathematical modeling of the gasket material is using the Maxwell Garnett (MG) multiphase formulation, developed in our papers [1, 2].

This formulation allows for taking into account multiple types (phases) of inclusions of any ellipsoidal geometry. The inclusions are randomly oriented in three-dimensional space. Phases of the mixture may have any frequency characteristics. The inclusions may be of any nature - dielectric, magnetic, magneto-dielectric, or conductive. As discussed further in this paper, inclusions with high permittivity and/or permeability have a tendency to concentrate electromagnetic energy which is then dissipated in nearby conductive particles through Ohmic losses. The basic restriction of the MG model is the quasistatic condition, that is, sizes of inclusions should be much smaller than the wavelengths in materials of inclusions. Another restriction is applicable if inclusions are conductive: their concentration should be below the percolation threshold, *i.e.*, the concentration where a dielectric abruptly turns into a conductor.

According to the MG formulation, if there is a mixture of different phases, the effective permittivity of the multiphase mixture is [1, 2]

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$$\varepsilon_{eff} = \varepsilon_b + \frac{\frac{1}{3}\sum_{i=1}^{n} v_i(\varepsilon_i - \varepsilon_b)\sum_{j=1}^{3}\frac{\varepsilon_b}{\varepsilon_b + N_{ij}(\varepsilon_i - \varepsilon_b)}}{1 - \frac{1}{3}\sum_{i=1}^{n} v_i(\varepsilon_i - \varepsilon_b)\sum_{j=1}^{3}\frac{N_{ij}}{\varepsilon_b + N_{ij}(\varepsilon_i - \varepsilon_b)}}, \quad (1)$$

where ε_b and ε_i are the relative permittivities of the base and inclusions, v_i is the volume fraction occupied by the inclusions of *i*-th type, and N_{ij} are the depolarization factors of inclusions. In the general case the inclusions are ellipsoids [1]. If the inclusion phase is metallic having conductivity σ, then its relative permittivity is

$$\varepsilon_m(j\omega) = \varepsilon' - j\varepsilon'' = \varepsilon' - j\frac{\sigma}{\omega\varepsilon_0}. \quad (2)$$

The base material might be quite transparent over the frequency range where high shielding effectiveness is desired. The behavior of many polymeric materials in the microwave range can be described by the Debye frequency dependence,

$$\varepsilon_b(j\omega) = \varepsilon_{\infty b} + \frac{\varepsilon_{sb} - \varepsilon_{\infty b}}{1 + j\omega\tau_b}. \quad (3)$$

In our paper [3], it was shown that combining dielectric or conducting inclusions with ferrite particles may substantially increase the absorption level in the frequency range of interest. At the same time, if there are only conducting inclusions in the base material, or if there are only ferrite particles in the base dielectric, energy absorption is comparatively low. The explanation for the increased absorption in a mixture of ferrite and conducting inclusions is the following. Ferrite particles concentrate electromagnetic energy in their vicinity due to their high permittivity and high permeability. Conducting particles in close proximity to the ferrite inclusions absorb this energy due to the currents induced in them and the resulting ohmic loss.

Ferrite inclusions have frequency dispersion resulting from both permeability and permittivity. For example, the real and imaginary parts of bulk NiZn ferrite complex permittivity and permeability behave according to the Debye law [4],

$$\varepsilon_f(j\omega) = \varepsilon_{\infty f} + \frac{\varepsilon_{sf} - \varepsilon_{\infty f}}{1 + j\omega\tau_{fe}};$$
$$\mu_f(j\omega) = 1 + \frac{\chi_s}{1 + j\omega\tau_{fm}}. \quad (4)$$

For composites containing randomly oriented ferrite particles whose size is greater than a magnetic domain, the effective permeability of the mixture is calculated in a simple way, as is shown in [5]. If the permeability of bulk polycrystalline ferrite $\mu_{f\ \mathrm{bulk}}$ is known, and a volume fraction of ferrite in a mixture with non-magnetic phase(s) is v_f, then the effective magnetic susceptibility of the mixture is calculated as

$$\mu_{eff} = 1 + \frac{2}{3}v_f\left(\mu_{f\ \mathrm{bulk}} - 1\right). \quad (5)$$

Ferrites belong to the group of magnetic ceramics. Their static (d.c.) dielectric constant is typically around 15-20. To increase the concentration of electromagnetic energy, it is reasonable to use inclusion particles with very high dielectric constant. This can be done by using barium titanate ceramics (BTC) together with or instead of ferrite particles. Some of the BTCs have high permittivity and, according to Kramers-Kronig relations [6], high dielectric loss over the microwave frequency range.

BTC is a dispersive material with permittivity that follows the Debye frequency dependence,

$$\varepsilon_{BT}(j\omega) = \varepsilon_{\infty b} + \frac{\varepsilon_{sBT} - \varepsilon_{\infty BT}}{1 + j\omega\tau_{BT}}. \quad (6)$$

For example, [7] describes the microwave coarse-grain BTC with static permittivity $\varepsilon_{s\,BT}$=1900, high-frequency permittivity $\varepsilon_{\infty BT}$=280, and relaxation frequency f_{rBT}=771 MHz, which corresponds to the Debye constant τ_{BT}=2.0642·10^{-9} s. In general, frequency dependencies of permittivity for different BTC types vary in a substantial range, depending on the BTC morphology (microstructure), regime of preparation, presence of impurities, pores, or dopant ions.

Herein, the frequency characteristics of real and imaginary permittivity and permeability components for a composite are modeled analytically. The composite is made of a low-lossy base (host) material (such as Teflon), ferrite particles (Ni-Zn or Mn-Zn), conductive particles (e.g., carbon or Al powder), and microwave BTC with the parameters described above. In Figures 1 and 2, the real and imaginary parts of the mixture's effective relative permittivity and permeability are plotted as functions of frequency. The resultant frequency dependence of the mixture's effective permittivity can be approximated by a curve having the following Debye parameters: $\varepsilon_{seff} = 100$, $\varepsilon_{\infty eff}$ = 70, τ_{eff} = 3.98·10^{-10}s, where the d.c. conductivity, responsible for the low-frequency loss, is $\sigma_{eff} = 10^{-3}$ S/m. These parameters were extracted using the optimization technique based on the genetic algorithm (GA) developed at UMR [2]. Complex permeability also follows the Debye dispersion law, and the corresponding magnetic Debye parameters are $\chi_{sf} = 44$, $f_{rf} = \dfrac{1}{2\pi\tau_{fm}}$=450 MHz.

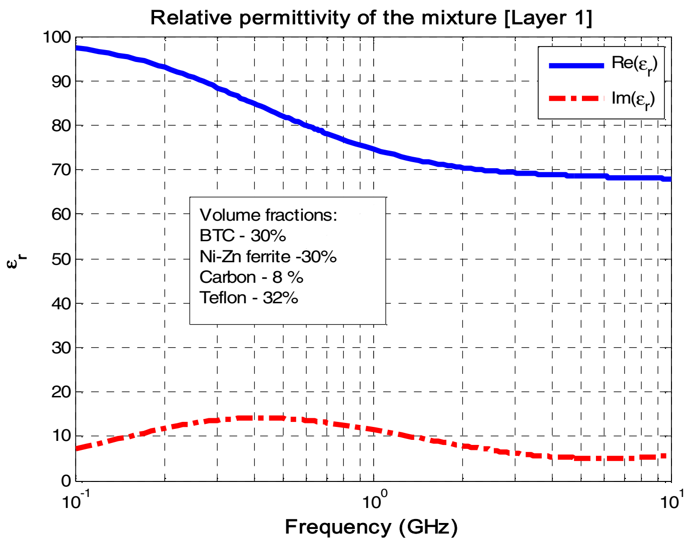


Figure 1. Permittivity of the mixture as a function of frequency. Constituents: Teflon (base): ε_{sb}=2.2, $\varepsilon_{\infty b}$=1.8, τ_b= $18{\cdot}10^{-11}$s; BTC (spheres): ε_{sBT}=1900, $\varepsilon_{\infty BT}$=280, τ_{BT}=$2.06{\cdot}10^{-9}$s; Ni-Zn ferrite (spheres): ε_{sf}=16, $\varepsilon_{\infty f}$=6, τ_{fe}= $7.95{\cdot}10^{-10}$s; Carbon (sticks): σ=10^5 S/m, $a = l/d$=50.

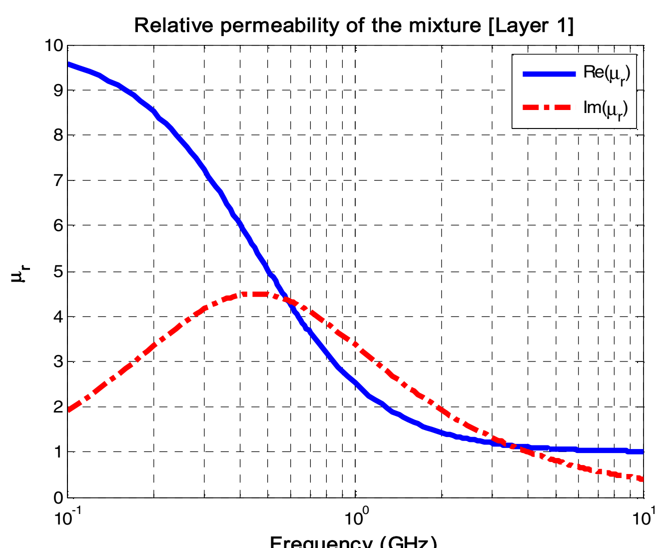


Figure 2. Permeability of the mixture as a function of frequency.

The mixture contains 30% of Ni-Zn ferrite with magnetic parameters: $\mu_{sf} = 45$, $f_{rf} = \dfrac{1}{2\pi\tau_{fm}}$=450 MHz.

Figure 3 shows the shielding effectiveness as a function of frequency for a 10-mm thick infinite layer of this material. This shielding effectiveness is obtained from a standard plane-wave formulation:

$$S.E._{\infty} = 20 \cdot \log\left(\frac{E_{inc}}{E_{tr}(t)}\right), \tag{7}$$

where t is the thickness of the layer.

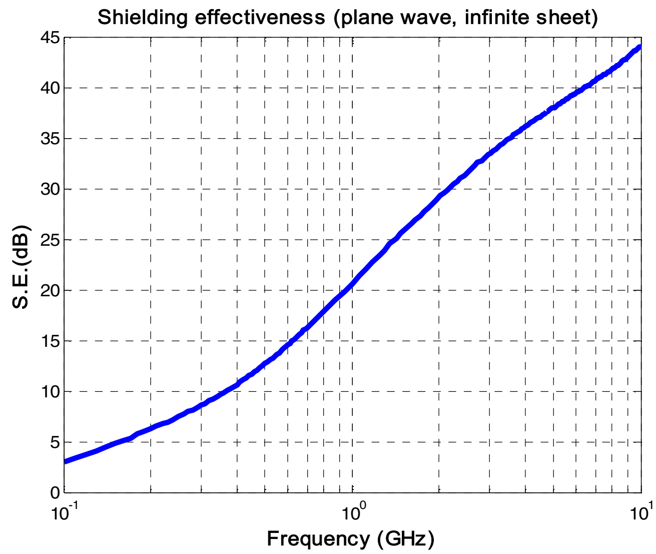


Figure 3. Shielding effectiveness of an infinite plane 10 mm –thick sheet of the absorbing material. Constituents as in Figures 1 and 2.

Varying the contents of a mixture (volume fractions of different inclusion types), physical parameters of the constituents $(\varepsilon_i, \varepsilon_b, \mu_i, \sigma)$, their shape and size, it is possible to change frequency characteristics as desired.

III. FDTD Modeling of Gasket Structure

The derived Debye frequency dependencies for the composite material, as shown in Fig. 1 and 2, are used in a full-wave FDTD numerical model of a gasket sandwiched between two Perfectly Electrically Conductive (PEC) plates.

The geometry under study is a shield comprised of two large (infinite) overlapping parallel metal plates with a gap between them, as shown in Figure 4. The gap thickness is *g* mm (*e.g*, 3 mm), and the overlapping width is *w* mm (*e.g.*, 50 mm). The gap is completely filled with an absorbing material having the synthesized frequency response. The parameter that shows how well the engineered gasket reduces the electromagnetic field penetrating through the structure is the shielding effectiveness. To determine the shielding effectiveness of the structure, it is assumed that a plane wave is incident upon the structure, and, for the sake of simplicity, that this wave is normally incident upon the structure, that is, the wave vector is perpendicular to the metal planes.

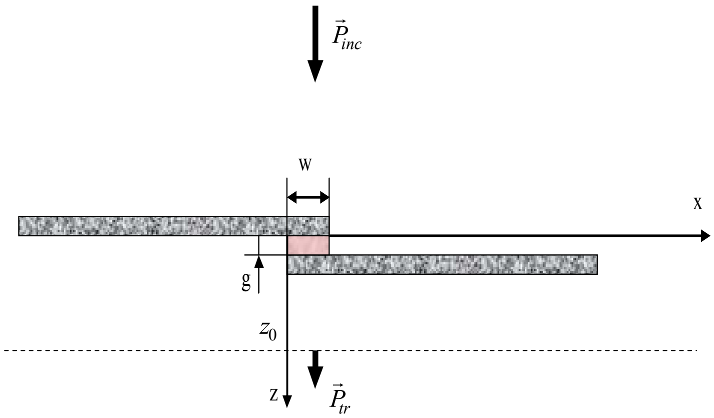


Figure 4. Geometry of the problem: w= 50 mm and g = 3 mm.

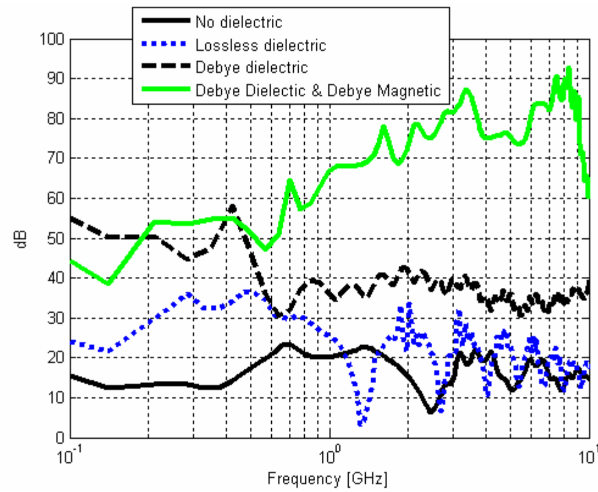
The shielding effectiveness is evaluated as

$$S.E._E = 20 \cdot \log\left(\frac{E_{inc}}{E_{tr}(z_0)}\right), \qquad (8)$$

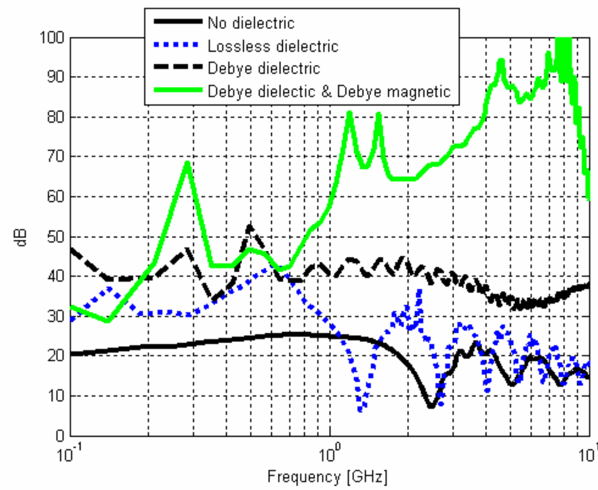
$$S.E._H = 20 \cdot \log\left(\frac{H_{inc}}{H_{tr}(z_0)}\right)$$

where E_{inc} and H_{inc} are the incident field's electric and magnetic field intensity, while $E_{tr}(z_0)$ and $H_{tr}(z_0)$ are the corresponding "transmitted" field intensities at the point of observation z_0 behind the shielding structure. It is important that the shielding effectiveness calculation is valid for a point of observation that is taken either in the near-field, or in the far-field region.

Figure 5 demonstrates the FDTD modeling results for the shielding effectiveness of the structure shown in Figure 4. In the FDTD model, the pseudo-wire source consists of multiple source lines. It is a Gaussian modulated source. The dimensions of the FDTD computational domain are 150mm x 500 mm x 230mm. The cell size for the FDTD model, corresponding to Figure 4, was $\Delta x = 1$ mm, $\Delta y = 1$ mm, and $\Delta z = 0.25$ mm. There are multiple line sources (modulated Gaussian) simulating a plane wave: they were 148 cells long in the *X*-direction, and 4 cells apart from each other in the *XY*-plane. E-field and H-field probes were placed 5 cells behind the structure (behind the gap) exactly centered in the *XY*- plane. The FDTD results in Figure 5 are obtained for four cases: (1) no dielectric -just air-filled gap between the PEC plates, (2) a lossless dielectric in the gap ($\varepsilon_r = 4.5$), (3) a Debye dielectric with the frequency dependence as shown in Figure 1, and (4) a material with both Debye dielectric and Debye magnetic frequency characteristics as shown in Figures 1 and 2.



(a)



(b)

Figure 5. The FDTD modeling of shielding effectiveness: (a) for electric field component; (b) for magnetic field component.

It is seen that the lossy Debye dielectric substantially increases the shielding effectiveness of the structure compared to the cases of an air gap between the PEC plates and gap filled with a lossless dielectric. The results from modeling the absorbing material as a Debye dielectric only substantially increases shielding effectiveness and makes the absorption characteristic wider. Adding a Debye magnetic medium (ferrite-carbon-BT mixture) further improves the absorptive properties of the gasket, and the shielding effectiveness substantially increases, especially at the frequency around 200 MHz and above 800 MHz. S.E. of the gasket with the Debye magneto-dielectric material in the frequency range over 1 GHz is 30-50 dB higher than for the Debye dielectric material for both electric and magnetic field components.

Varying the individual inclusions comprising the composite gasket material allows for controlling and damping levels of the "transmitted" electromagnetic field power. Shielding effectiveness also depends on the geometry of the gasket – its dimensions and configuration (*e.g.*, the absorbing material inside the gap may be meander shaped).

IV. CONCLUSION

The presented analytical model allows for engineering a suitable material for a gasket that will substantially reduce radiation from the gap between two overlapping metal plates in the given frequency range (within the microwave band). The model is suitable for implementation in a full-wave numerical modeling (FDTD) tool. The geometry that contains this gasket material is modeled. The results of computations show a substantial increase in the structure's shielding effectiveness, where the structure consists of two overlapping metal plates and an engineered composite magneto-dielectric material gasket in the gap between these plates, compared to the case of overlapping plates without any absorbing gasket.

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