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Modeling of ferrite-based materials for shielding enclosures

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Abstract

An analytical model for a magneto-dielectric composite material is presented based on the Maxwell Garnett rule for a dielectric mixture, and on Bruggeman’s effective medium theory for permeability of a ferrite powder embedded in a dielectric. In order to simultaneously treat frequency-dispersive permittivity and permeability of a composite in a full-wave FDTD code, a new algorithm based on discretized auxiliary differential equations has been implemented. In this paper, numerical examples of modeling structures containing different magneto-dielectric mixtures are presented.

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1. Introduction

The design of non-conductive, energy absorbing shielding enclosures and gaskets for improving immunity of electronic equipment is important, especially from the point of view of eliminating possible surface currents as culprits of undesirable emission. It has been found that combining dielectric, ferrite, and conductive inclusions in a composite may substantially increase the absorption for a given frequency range.

This paper presents an analytical model of a magneto-dielectric material with both frequency-dispersive permittivity and permeability, and a full-wave numerical model of a shielding structure that contains this magneto-dielectric material. The numerical model employs EZ-FDTD code developed by Missouri University of Science and Technology (MS&T) based on the finite-difference time-domain technique [1]. To simultaneously treat frequency-dispersive permittivity and permeability, a new algorithm based on auxiliary differential equations, discretized both in space and in time, has been implemented.

2. Analytical model of a composite magneto-dielectric material

The analytical model employed is based on the Maxwell Garnett (MG) rule for a multiphase dielectric mixture with ellipsoidal inclusions in the general case [2], and also employs Bruggeman’s effective medium theory (BEMT) for permeability of a ferrite powder embedded in a dielectric host [3]. If there are conducting inclusions with intrinsic conductivity \( \sigma \) in the mixture, their relative permittivity is \( \varepsilon_{rel} = \varepsilon - j\omega\varepsilon_0\sigma \). The behavior of a base material (e.g., a polymeric dielectric) in the microwave range can be described by the Debye frequency dependence.

In order to increase the concentration of electromagnetic energy in an absorbing-type material, it is reasonable to add a phase with high permittivity over the microwave frequency range, for example, barium titanate ceramics (BTCs). Frequency dependencies of permittivity for different BTCs vary over a wide range, depending on the BTC microstructure, regime of preparation, presence of impurities, pores, or dopant ions. For example, Ref. [4] describes the coarse-grain BTC with the Debye parameters \( \varepsilon_{\text{BTC}} = 1900 \), \( \varepsilon_{\text{BTC}} = 280 \), and \( f_{\text{BTC}} = 771 \text{MHz} \), corresponding to \( \tau_{\text{BTC}} = 2.06 \times 10^{-13} \text{s} \).

If there are only conductive inclusions, or only ferrite particles in the base, energy absorption is relatively low. The combination of dielectric or conductive inclusions with ferrite particles has been found to substantially increase the absorption [5]. Ferrite particles serve as local concentrators of electromagnetic energy within the base material. Conducting particles in close proximity to the ferrite inclusions absorb this localized energy due to the ohmic loss. In order to take advantage of the cooperative effect between the ferrites and the conducting particles, an absorbing material containing the two is investigated.
The permeabilities and permittivities of ferrites are considered frequency-dispersive \([6]\),

\[
\varepsilon_f(j\omega) = \varepsilon_{\text{ef}} + \frac{\varepsilon_d - \varepsilon_{\text{ef}}}{1 + j\omega\tau_f},
\]

(1)

\[
\mu_f(j\omega) = 1 + \frac{x_0}{1 + j\omega\tau_{\text{im}}},
\]

(2)

It is known that for dielectric mixtures with spherical inclusions, Bruggeman’s formula can be derived through differential analysis, and it contains permittivities to the \(\frac{29}{10}\) power \([3]\). Using both of the dielectric and magnetic mixing rules, Bruggeman’s rule can be written for effective permeability as

\[
\frac{\mu_i - \mu_{\text{eff}}}{\mu_i} = (1 - \nu_i)\left(\frac{\mu_{\text{eff}}}{\mu_0}\right)^{1/3}.
\]

(3)

The permeability \(\mu_i\) of a powdered ferrite is different from the permeability of the initial bulk ferrite. If the bulk ferrite is crushed to a powder with particle size greater than a magnetic domain, and then particles are glued together such that the ferrite volume fraction remains close to \(\nu_i = 1\) (with allowance for the small gaps between the particles), the resultant permeability can be approximated as

\[
\mu_i \approx \frac{\mu_{\text{bulk}}}{1 + a\cdot\mu_{\text{bulk}}}
\]

(4)

where \(a = \langle \text{agap} \rangle / \langle d \rangle\) is the ratio of average distance between neighboring particles and average diameter of the particles. Fig. 1 shows some curves for \(\mu_i\) as a function of \(a\) for different bulk permeabilities.

These estimations agree with the data in Refs. \([7-9]\). It is seen that when \(a = 0\), then \(\mu_i \rightarrow \mu_{\text{bulk}}\). Eq. (2) can be rewritten as

\[
x^3 + bx - a = 0,
\]

(5)

with \(\mu_{\text{eff}} = x^3\), \(a = \mu_i\) and \(b = (1-\nu_i)(a-1)\). This equation solved for \(x\) has three roots. The only real, positive solution is

\[
x = \sqrt[3]{\frac{108a + 12\sqrt[3]{12b + 81a^2}}{108a + 12\sqrt[3]{81a^2}}}
\]

(6)

This model \((3)-(6)\) agrees well with the experimental data in Refs. \([10,11]\) for iron-based powders. In addition, for Mn–Zn ferrites with \(\mu_{\text{bulk}} = 1700\) and \(a = 10^5\), the calculated permeability is \(\mu_i = 630\). For 40% volume fraction of this ferrite, the calculated static \(\mu_{\text{eff}} = 4.3\) agrees well with the Steward data \([12]\). At the same time, the MG rule for permeability \([10]\) gives the lowest limit of \(\mu_{\text{eff}} = 2.9\), whereas logarithm Eq. \([13]\) yields \(\mu_{\text{eff}} = 5.2\), and the upper Hashin–Shtrikman limit \([14]\) turns out to be \(\mu_{\text{eff}} = 29.8\). The above formulas are valid for ferrite inclusions of spherical shape. If magnetic needles or discs (platelets) are utilized, then demagnetization factors should be included in the formulation for correcting the calculated effective permeability.

Figs. 2 and 3 present frequency characteristics of effective permittivity and permeability for several composites. Different materials in the composite include a Teflon-like host material, spinel ferrite and microwave BT powders, conductive particles (e.g., graphite), in addition to other contents that are beyond the scope of this paper. These are the curves modeled using the described above methodology.

Shielding effectiveness (S.E.) in terms of plane-wave electric \((E)\) or magnetic field \((H)\) is defined as

\[
S.E_{E,H}(\omega) = 20 \cdot \log \left( \frac{E_{\text{in}}(0)}{E_{\text{in}}(\omega)} \right).
\]

(7)
where \(0\) is reference point for the incident field, and \(z\) is the observation point of in the chosen direction (typically the direction of wave propagation). Fig. 4 demonstrates S.E. for an infinitely wide (2D) sheets of composite materials. The thickness of the sheets is defined as \(d = 3\) mm. Their effective parameters correspond to the curves in Figs. 2 and 3. Relative permittivity of the Debye dielectric shown in Fig. 4 is the same as for Composite 3, but its magnetic susceptibility is zero.

3. Debye dielectric and magnetic materials simulation in FDTD

An advantage of time-domain solvers, such as the FDTD [16], over their frequency-domain counterparts is the ability to extract wideband frequency response via a short pulse excitation. Frequency characteristics of linear dispersive materials can be approximated by series of Debye terms [1]. The main methods in FDTD for treating a Debye material include the piecewise-linear recursive convolution (PLC), and the auxiliary differential equations (ADE) [16]. In our EZ-FDTD code, the ADE method is adopted to simulate double-Debye materials (DDM) with relative parameters

\[
\varepsilon_r(\omega) = \varepsilon_\infty + \sum_{p=1}^{P} \frac{\varepsilon_p - \varepsilon_\infty}{1 + j\omega \tau_p^e} = \varepsilon_\infty + \sum_{p=1}^{P} \varepsilon_p^e,
\]

\[
\mu_r(\omega) = \mu_\infty + \sum_{p=1}^{P} \frac{\mu_p - \mu_\infty}{1 + j\omega \tau_p^m} = \mu_\infty + \sum_{p=1}^{P} \mu_p^m,
\]

where \(\varepsilon_\infty\) and \(\mu_\infty\) are the “optic-limit”, and \(\varepsilon_p^e\) and \(\mu_p^m\) are the \(p\)th-term static permittivity and permeability. The relaxation times are \(\tau_p^e\) and \(\tau_p^m\), respectively. Substituting Eq. (8) in the ADE [16] yields the following finite difference time-domain scheme for an H-field loop

\[
\mathbf{H}^{n+1} = \frac{2\mu_0[\mu_\infty + \sum_{p=1}^{P} \mu_p^m] - \mu_0 \Delta t}{2\mu_0[\mu_\infty + \sum_{p=1}^{P} \mu_p^m] + \mu_0 \Delta t} \mathbf{H}^n + \left( \frac{2\mu_0[\mu_\infty + \sum_{p=1}^{P} \mu_p^m]}{2\mu_0[\mu_\infty + \sum_{p=1}^{P} \mu_p^m] + \mu_0 \Delta t} \right) \\
\times \nabla \times \mathbf{E}^n - \frac{1}{2} \sum_{p=1}^{P} (1 + k_p \mathbf{M}_p^e),
\]

Similarly, for an E-field loop, the difference scheme is

\[
\mathbf{E}^{n+1} = \frac{2\varepsilon_0[\varepsilon_\infty + \sum_{p=1}^{P} \varepsilon_p^e] - \varepsilon_0 \Delta t}{2\varepsilon_0[\varepsilon_\infty + \sum_{p=1}^{P} \varepsilon_p^e] + \varepsilon_0 \Delta t} \mathbf{E}^n + \left( \frac{2\varepsilon_0[\varepsilon_\infty + \sum_{p=1}^{P} \varepsilon_p^e]}{2\varepsilon_0[\varepsilon_\infty + \sum_{p=1}^{P} \varepsilon_p^e] + \varepsilon_0 \Delta t} \right) \\
\times \nabla \times \mathbf{H}^n - \frac{1}{2} \sum_{p=1}^{P} (1 + k_p \mathbf{M}_p^m) + \frac{2\mu_0[\mu_\infty + \sum_{p=1}^{P} \mu_p^m]}{2\mu_0[\mu_\infty + \sum_{p=1}^{P} \mu_p^m] + \mu_0 \Delta t} \mathbf{H}^n,
\]

with auxiliary magnetic and electric sources introduced for each Debye term

\[
\mathbf{M}_p^e = k_p^e \mathbf{M}_p^m + 2\mu_0 \mathbf{M}_p^m \left( \frac{\mathbf{H}^{n+1} - \mathbf{H}^n}{\Delta t} \right)
\]

and

\[
\mathbf{E}_p^m = 2\varepsilon_0 \mathbf{M}_p^m + \frac{\varepsilon_0 \Delta t}{2} \mathbf{E}^n - \varepsilon_0 \mathbf{M}_p^m \left( \frac{\mathbf{H}^n}{\Delta t} \right)
\]
\[
J_{n+1}^p = k_p^e J_{n+1}^e + 2 \varepsilon_0 B_p^e \left( \frac{E_{n+1}^e - E_n^e}{\Delta t} \right),
\]
(11)

where \( \Delta t \) is the time step for the difference approximation for differential operators in FDTD. The auxiliary parameters in Eq. (11) are

\[
k_h^p = \frac{2 \sigma_h^p - \Delta t}{2 \sigma_h^p + \Delta t};
\]

\[
\beta_h^p = \frac{(\mu_h^p - \mu_m^p) \Delta t}{2 \sigma_h^p + \Delta t};
\]

\[
k_e^p = \frac{2 \sigma_e^p - \Delta t}{2 \sigma_e^p + \Delta t};
\]

\[
\beta_e^p = \frac{(\varepsilon_h^p - \varepsilon_m^p) \Delta t}{2 \sigma_e^p + \Delta t};
\]

(12)

where \( \sigma_h^p \) and \( \sigma_e^p \) are the electric and magnetic “conductivities” [16]. Treatment of interfaces between DDM cells and other types of materials is similar to that of ordinary dielectrics [17], but the auxiliary sources \( M_p \) and \( J_p \) require processing by an averaging along the interface of different materials to assure for the continuity of tangential fields.

The structure shown in Fig. 5 has been modeled using the EZ-FDTD codes. The structure contains a DDM strip 50 mm wide and 3 mm thick in the space between the two large overlapping metal (perfect electric conductor) plates. The corresponding Debye curves used in the numerical modeling were extracted from the curves in Fig. 2 and 3 using the genetic algorithm optimization [15]. The computations (Fig. 6) show a substantial increase in the shielding effectiveness (S.E.) of the structure compared to the cases of overlapping plates without any absorbing material, or with a Debye dielectric exhibiting the same permittivity as the effective permittivity of the modeled magneto-dielectric material.

The trend in increasing S.E. for this structure is similar to the trend in Fig. 4 for 2D sheets.

4. Conclusion

This paper presents analytically modeled “double-Debye” magneto-dielectric materials, and a full-wave numerical model of a shielding structure that contains this material. To simultaneously treat frequency-dispersive permittivity and permeability, a new algorithm based on auxiliary differential material equations, discretized both in space and in time, has been implemented. The results of computations show a substantial increase in shielding effectiveness when using a double-Debye material.

References