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AN ANALYTICAL APPROACH FOR MATERIAL SYNTHESIS BASED ON SHIELDING EFFECTIVENESS CHARACTERISTICS

Cihan DÖĞÜŞGEN (ERBAŞ) *
Sedef KENT **

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Abstract: We describe an analytical method to synthesize a Debye-like equivalent homogeneous material by computing the associated parameters such as static relative permittivity, relative high-frequency limit permittivity, relaxation time, and the width of the material for a given shielding effectiveness specification and a given range of frequency as well as material width. We illustrate the parameter extraction procedure with a numerical example, in which we validate that the applied method is able to produce the desired SE profile within the specified frequency range.

Keywords: Shielding effectiveness, Material synthesis, Debye parameters, homogeneous material, composite material

Ekranlama Verimliliği Karakteristiği Baz Alınarak Madde Sentezlenmesi için Analitik Bir Yaklaşım

Öz: Verilen bir ekranlama verimliliği karakteristiği ile frekans ve madde genişliği aralığı için, statik göreceli permitivite, göreceli yüksek frekans limiti permitivitesi, relaksasyon zamanı ve madde genişliği gibi ilgili parametreleri hesaplayarak Debye-benzeri eşdeğer homojen madde sentezlenmesi için bir analitik metod tasvir etmekteyiz. Parametre çıkarım prosedürünü, uygulanan metodun belirlenen frekans aralığında, istenen ekranlama verimliliği profilini üretebildiğini doğruladığımız bir sayısal örnekle anlatmaktayız.

Anahtar Kelimeler: Ekranlama verimliliği, madde sentezi, Debye parametreleri, homojen madde, kompozit madde

1. INTRODUCTION

Electronic devices are usually protected in conducting shields to prevent the electronics inside the shield from radiating emissions and/or prevent the electromagnetic fields outside the device from coupling to the electronics inside the shield (Mississippi State University, 2015). Performance of the shield is represented by the term *shielding effectiveness (SE)*, whose mathematical definition is shown in Section 2.

Composite materials are becoming more important as they are increasingly used in applications such as electromagnetic shielding, heat transfer and isolation as well as mechanical support purposes (De Rosa et. al., 2009). These materials are constituted by combining multiple materials with various electrical and physical characteristics. There are several ways to

* Istanbul Yeni Yuzyıl University, Electrical and Electronics Engineering Department, Yilanli Ayazma Street 26, Cevizlibag, Zeytinburnu, Istanbul, 34010, Turkey
** Istanbul Technical University, Electronics and Communication Engineering Department, Maslak, Istanbul, Turkey
Correspondence Author: Cihan Dogusgen (Erbas) (cihan.dogusgen@yeniyuzyil.edu.tr)

investigate the performance of composite materials (Ouchetto et. al., 2006), (Lagarkov and Sarychev, 1996), (Nisanci et. al., 2012).

In this study, we focus on synthesis of homogeneous materials, which is the preliminary step for synthesizing composite materials (it is possible to synthesize a realistic composite material from the equivalent homogeneous one (Nisanci et. al., 2011)). We start with a specified SE definition for a given frequency and material width ranges. We apply an analytical method to compute the equivalent homogeneous material parameters from that SE specification. We calculate the the width of the material along with the Debye parameters such as static relative permittivity, relative high-frequency limit permittivity, relaxation time. Finally, we give a numerical example to illustrate the process.

2. EFFECT OF THE DEBYE PARAMETERS OF HOMOGENEOUS MATERIAL ON SE

The SE of a material with a thickness W (shown in Figure 1) is defined as

$$SE = -20log_{10}(|T|) \tag{1}$$

where T is the transmittance, which is a function of the propagation constant γ_m, reflection and transmission coefficients of the first and second boundaries (of the material with a width of W), $R_{1,2}$ and $T_{1,2}$ respectively. These parameters (for an arbitrary incidence angle and for perpendicular polarization) are defined as

$$T = \frac{T_1 T_2 e^{-\gamma_m W}}{1+R_1 R_2 e^{-2\gamma_m W}} \tag{2}$$

$$\gamma_m = j\omega\sqrt{\mu_0\varepsilon_0}\sqrt{\varepsilon_D} \tag{3}$$

$$R_1 = \frac{Z_m cos\theta_1 - Z_0 cos\theta_2}{Z_m cos\theta_1 + Z_0 cos\theta_2} \tag{4}$$

$$R_2 = \frac{Z_0 cos\theta_2 - Z_m cos\theta_3}{Z_0 cos\theta_2 + Z_m cos\theta_3} \tag{5}$$

$$T_1 = 1 + R_1 \tag{6}$$

$$T_2 = 1 + R_2 \tag{7}$$

In Equations (3)-(7), Z_0 and Z_m are the characteristic impedances in air and in the medium, respectively. Angular frequency is denoted by ω. ε_0 and μ_0 are the vacuum permittivity and vacuum permeability, respectively. Θ_1 is the incidence angle. Θ_2 and Θ_3 are the transmission angles for the material and the air, respectively. ε_D corresponds to the complex, frequency dependent relative permittivity of the equivalent homogeneous material defined by the Debye model given as

$$\varepsilon_D = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1+j\omega\tau} \tag{8}$$

where ε_S is the is the static relative permittivity. τ and ε_∞ are called the relaxation time and the relative permittivity at high-frequency limit, respectively. To better understand the impact of Debye parameters of the homogeneous materials on the SE, we give a numerical example: Figure 2 illustrates the frequency-dependent SE for a number of panels with different permittivities and the same width (W=4 mm). We examine two cases for incidence angles of zero and 30 degrees, as illustrated in Figure 2. In both cases ($\theta_1=0^\circ$ and $\theta_1=30^\circ$), we examine the SE variation for a constant material permittivity of ε_r=290, and for the Debye parameters of

ε_S=290, ε_∞=30, and τ=(3.16).10^{-9}. From Figure 2, we realize that the Debye case has another SE maximum value and a minimum after reaching the first maximum within the frequency of interest. Those maximums and the minimum of SE are computed as (De Paulis et. al., 2014) 9.38 dB and 2.18 dB, respectively (for θ_1=0°), along with 10.53 dB and 2.47 dB, respectively (for θ_1=30°). For the constant material permittivity case, first maximum level is 18.63 dB for θ_1=0°, and 19.87 dB for θ_1=30°. Figure 3 shows the Debye permittivity in dB against frequency.

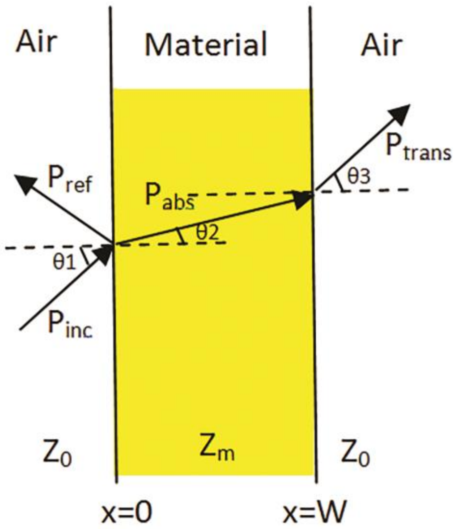

Figure 1:
Geometry of homogenized material with a thickness W where incident (P_{inc}), reflected (P_{ref}), absorbed (P_{abs}) and transmitted (P_{trans}) powers are denoted by associated arrows. Characteristic impedances in air and in material are given as Z_0 and Z_m, respectively.

Another example has the Debye parameters of ε_S=290, ε_∞=30, and τ=(3.16).10^{-10} for (θ_1=0° and θ_1=30°). For those parameters, Figure 4 and Figure 5 illustrate the SE and the Debye permittivity versus frequency, respectively. The incidence angle does not cause any difference in Debye permittivity in Figure 5, as the Debye permittivity is independent of incidence angle.

3. HOMOGENEOUS MATERIAL SYNTHESIS

In order to constitute the equivalent homogeneous material, we evaluate ε_S, ε_∞, τ and W through pre-defined values of SE, lower and upper frequency limits, a range of panel thickness W, and the parameter b∞, which is related to the shape of the SE profile (De Paulis et. al., 2014). The procedure is as follows: We extract the relaxation time through the following equation:

$$f_{ri} = \frac{1+\sqrt{2}}{2\pi\tau} \tag{9}$$

In Equation (9), f_{ri} is the frequency at which the imaginary part - real part difference of the Debye permittivity is maximum, and it corresponds to the lower end of the frequency range, which is a known value. Then we extract the Debye ε_∞ permittivity using Equation (10):

$$\left|T_{SE\_\max\_\infty}\right| = \frac{4\sinh(b_\infty)\varepsilon_\infty + 2cosh(b_\infty)\sqrt{\varepsilon_\infty}(\varepsilon_\infty+1)}{[4(\cosh(b_\infty)^2-1)\varepsilon_\infty + cosh(b_\infty).[4\sinh(b_\infty)\sqrt{\varepsilon_\infty}(\varepsilon_\infty+1)+cosh(b_\infty)(\varepsilon_\infty+1)^2]]} \tag{10}$$

where $T_{SE\_max\_\infty}$ is the limit value of the maximum transmittance, which is known from the initial values of SE. The parameter b_∞ has a pre-defined value that depends on the SE variation (against frequency). The remaining parameters to compute are ε_S and W. By using Equations (11) and (12), it is possible to calculate those parameters (ε_S and W).

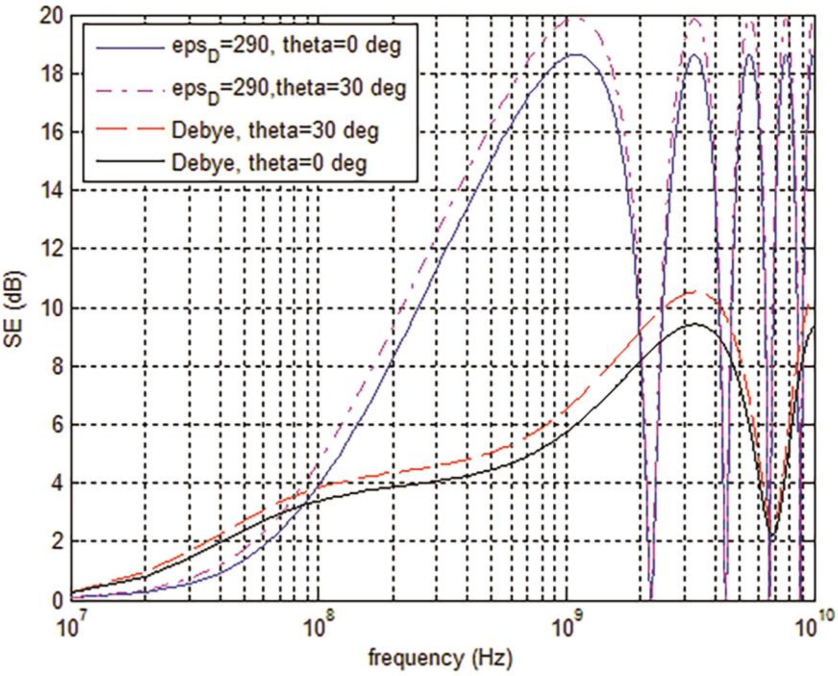

Figure 2:
SE plots for ε_r =290 and for the Debye parameters of ε_S=290, ε_∞=30, τ=(3.16).10^{-9}.Incidence angles of $\theta_1=0^\circ$ and $\theta_1=30^\circ$ are examined.

$$f_n = \frac{\sqrt{2}c_0.(2n+1)}{4W\sqrt{|\varepsilon_D|+\varepsilon_{Re}}} \quad , n=0,1,2,3... \tag{11}$$

$$b_\infty = \frac{(\varepsilon_S-\varepsilon_\infty)W}{2c_0\tau\sqrt{\varepsilon_\infty}} \tag{12}$$

In Equation (11), f_n is the frequency at which the maxima of SE occurs, c_0 =3.10^8 m/sec, and ε_D is the homogenized permittivity denoted by $\varepsilon_D = \varepsilon_{Re} - j\varepsilon_{Im}$. Taking into account the Debye dependence of ε_D, ε_{Re} and ε_{Im} can be expressed as

$$\varepsilon_{Re} = \frac{\omega^2\tau^2\varepsilon_\infty+\varepsilon_S}{1+\omega^2\tau^2} \tag{13}$$

$$\varepsilon_{Im} = \frac{\omega\tau(\varepsilon_S-\varepsilon_\infty)}{1+\omega^2\tau^2} \tag{14}$$

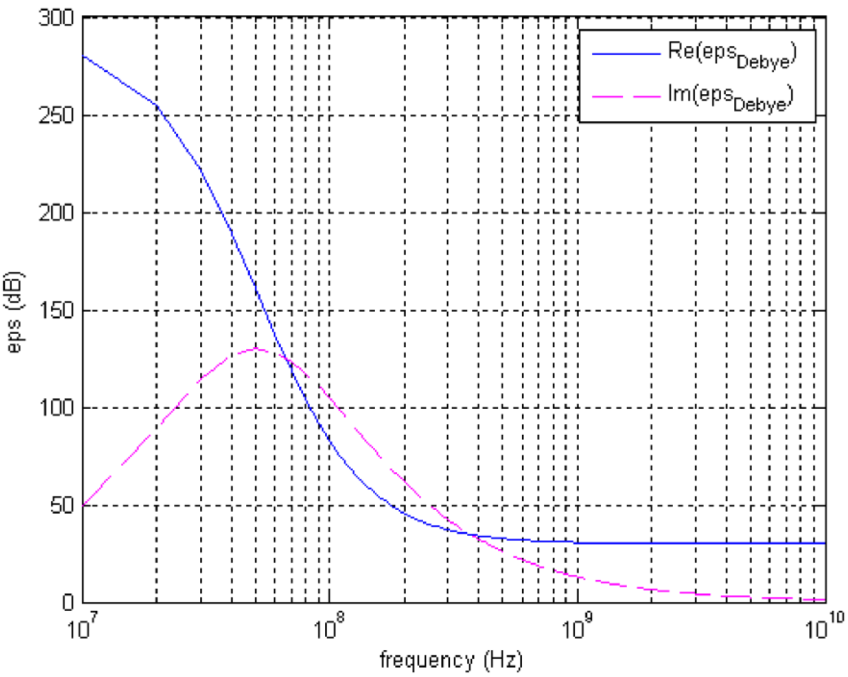

Figure 3:

Real part/imaginary part of the Debye permittivity computed for ε_S=290, ε_∞=30, τ=(3.16).10^{-9}.

To illustrate the homogeneous material synthesis process, we consider a numerical example with the following requirements:

SE > 12 dB

Low frequency = 48 MHz

High frequency = 6 GHz

1 mm < Material width (denoted by W) < 4 mm

where ω is the angular frequency. Equation (2) can be rearranged as

$$T(\varepsilon_D) = \frac{2\sqrt{\varepsilon_D}}{2\sqrt{\varepsilon_D}\cos\left(\frac{\omega W\sqrt{\varepsilon_D}}{c_0}\right)+j(1+\varepsilon_D)sin\left(\frac{\omega W\sqrt{\varepsilon_D}}{c_0}\right)} \quad (15)$$

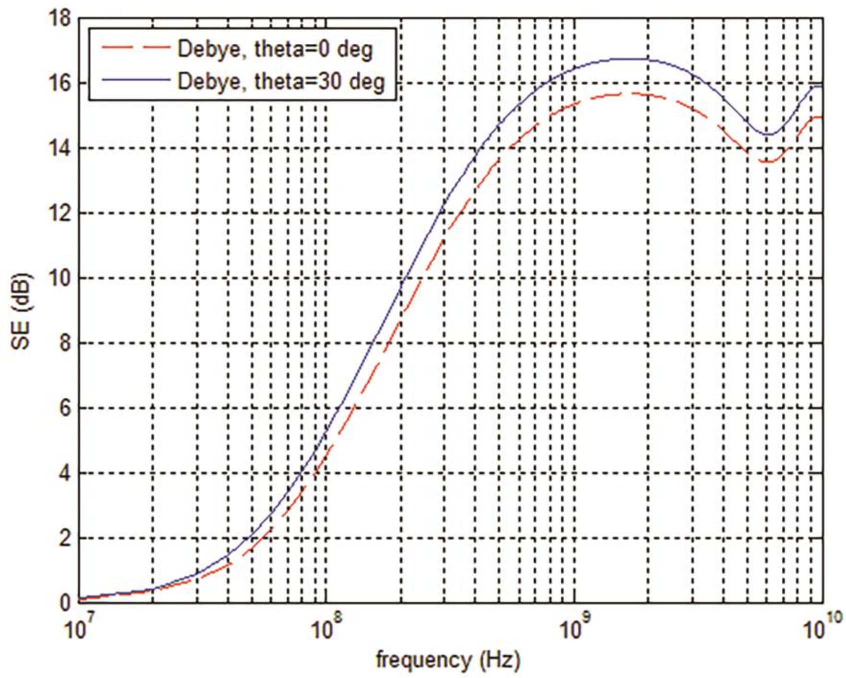

Figure 4:
SE against frequency calculated for the Debye parameters of ε_S*=290,* ε_∞*=30, and* $\tau=(3.16).10^{-10}$.
Incidence angles of $\theta_1=0^\circ$ and $\theta_1=30^\circ$ are examined.

From the above specifications, it is clear that the SE level should be greater than 12 dB between 48 MHz and 6 GHz. Upon examining the SE profile in Figure 2, $b_\infty<0.8$ would be appropriate for this example. We choose $b_\infty=0.75$, which would produce a fairly flat SE variation between the given frequency limits. Using f_{ri}=48 MHz in Equation (9) results in a Debye relaxation time of τ=8 nsec. We compute the Debye ε_∞ permittivity as $\varepsilon_\infty=21.77$ through Equation (10) with $b_\infty=0.75$ and SE_{max_∞} =12 dB. We utilize Newton method (Isaacson and Keller, 1994) with a tolerance of 10^{-6} and an initial value of 12 in order to extract ε_∞ through Equation (10). The computation process converges after 9 iterations. Then we simultaneously solve Equation (11) and Equation (12) for ε_S and W. Note that in Equation (11), $f_{n=0}$ =6 GHz. We obtain $\varepsilon_S=6979.30$ and W=2.4 mm.

The synthesized homogeneous material has the following parameters: $\varepsilon_S=6979.30$, $\varepsilon_\infty=21.77$, τ=8 nsec and W=2.4 mm. Figure 6 illustrates the SE as a function of frequency computed through Equation (15) by using the four parameters of the synthesized material. A flat SE profile is visible (about 13 dB) between f_{ri} and $f_{n=0}$, which meets the design criterion. Limit value of the maximum SE is computed as 12.04 dB.

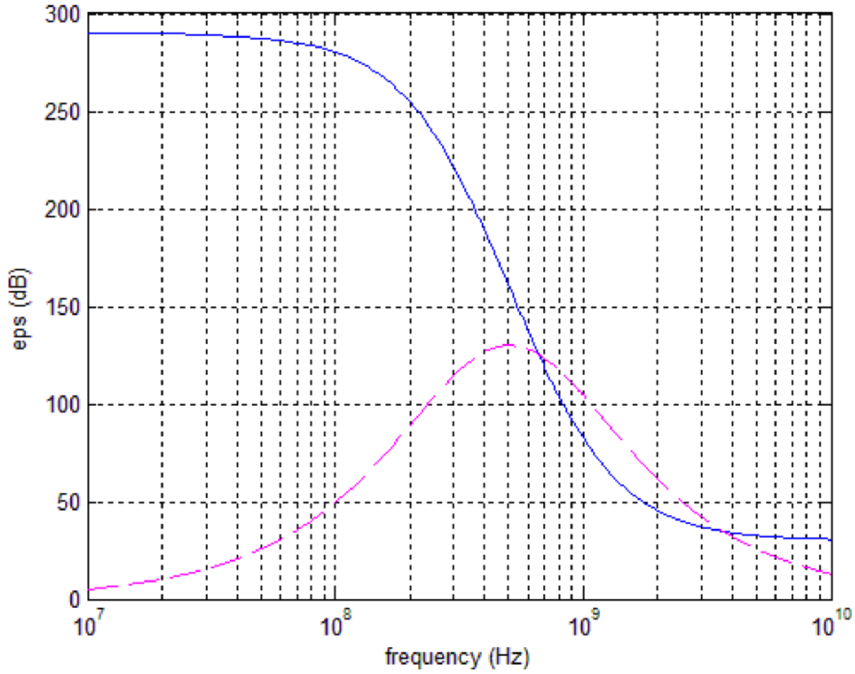

Figure 5:
Real and imaginary parts of Debye permittivity calculated for ε_S=290,ε_∞=30 and τ=(3.16).10^{-10}.

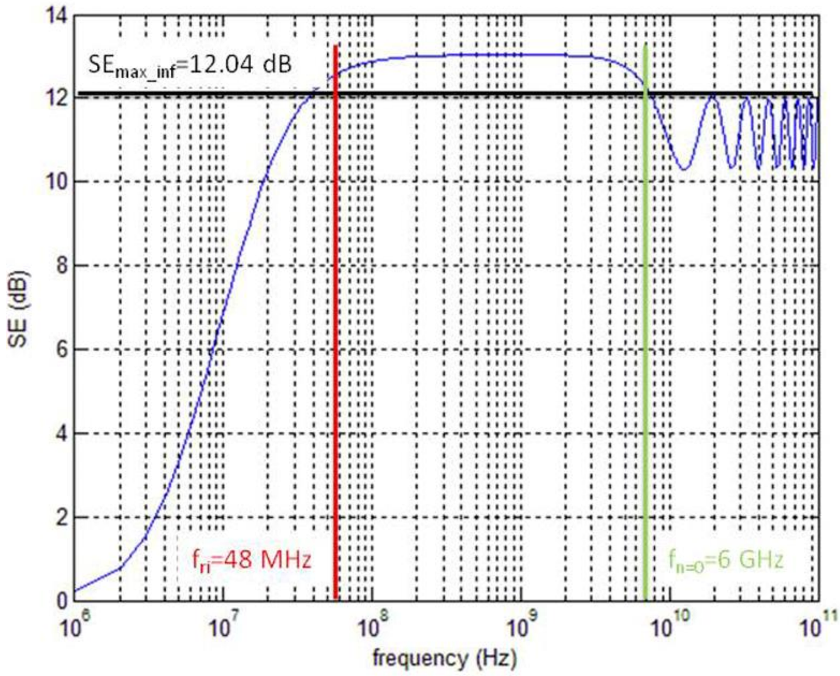

Figure 6:
Validation for the numerical example through Equation (15).

4. CONCLUSION

We present an analytical technique to evaluate the Debye parameters of an equivalent homogeneous material (along with the material width), which corresponds to the synthesis of the homogeneous material. We provide a numerical example that confirms the applied procedure is able to meet the design requirements. We carry out our analysis for arbitrary incidence angles. Our results could be a starting point for the synthesis of composite materials with more complicated geometries.

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