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Simulation-Driven Evaluation of Shielding Effectiveness in HDPE-Aluminum Nanoparticles Composites Using COMSOL

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ABSTRACT

To the purpose of this paper, we focus our attention on examining the electromagnetic interference (EMI) shielding effectiveness (SE) of high-density polyethylene (HDPE) composites filled with aluminum nanoparticles. By means of COMSOL Multiphysics for modeling and simulation, we attempt to compute the SE within 8 to 12 GHz. The purpose here is to characterize the shielding effectiveness of aluminum nanoparticles composite for further use in electronics and communication devices. The findings indicate that there are profound changes in the SE with frequencies, and there are certain GHz bands where the SE is minimized. These results may be beneficial for further improvement of the materials aimed to be used for EMI shielding in the GHz range.

Keywords: EMI shielding, aluminum nanoparticles, shielding effectiveness, composite materials, COMSOL Multiphysics, GHz frequencies

1. Introduction

Electromagnetic interference commonly known as EMI has turned out to be a major concern in the current electronic systems mainly arising from the need to develop communication systems with higher frequencies. As device work in the GHz ranges, shielding material become an essential requirement in the construction of products. Conductive polymer composites filled with aluminum nanoparticles and similar materials are potentially ideal for EMI shielding since they integrate numerous advantageous features including low density and relatively low price as well as the ability to adjust the characteristics of the material by varying the frequency.

This paper explores the shielding effectiveness SE of high-density polyethylene HDPE with aluminum nanoparticles using the COMSOL Multiphysics software to model the material's interaction with electromagnetic interference EMI operating at a frequency of 8-12 GHz. Shielding effectiveness is defined as the loss of power incident on the composite material divided by the power transmitted through it. More specifically, this work deals with the properties of aluminum nanoparticles and the description of the frequency-dependent behavior of those materials.

2. Materials and Methodology

2.1. Materials

The materials used in this present work are; high density polyethylene (HDPE) as the matrix material and aluminum nanoparticles as the conductive filler. The nanoparticles improve the shielding effectiveness of the composite by allowing the incident electromagnetic waves to be reflected, absorbed, and scattered. Aluminum nanoparticles are chosen for this work because they offer high electrical conductivity and low density that can be effective in the development of light weight shielding applications.

2.2 Simulation Setup

The simulation was performed with the COMSOL Multiphysics, an Finite element method FEM-based software suitable for precise modeling of distribution of electromagnetic fields and responses of materials. The model setup included the following:

- A rectangular shaped geometry of composite material where aluminum nanoparticles are dispersed in an HDPE matrix.
- The physical dimensions of the composite were held fixed while the frequency of incident electromagnetic waves was varied between 8 GHz and 12 GHz.

- The boundary conditions of the composite model involved the application of an incident plane wave on one side of the composite, while the other side of the model was set as a Perfect Electrical Conductor (PEC) to reflect any radiation that was not absorbed by the composite.

2.3 Calculating Shielding Effectiveness (SE)

The shielding effectiveness (SE) is defined by the following formula:

$$S.E = 10\ log\left(\frac{P_i}{P_o}\right)$$

Where

P_i = Power that is incident on the material

P_o= Transmitted power after passing through the shielding material

In the case under analysis, in order to estimate the efficiency of the implemented material, the SE on each of the identified frequency levels has been computed.

3. Results and Discussion

The SE simulation results of the designed shielding material for the frequency range 8 to 12 GHz are presented in Table 1 below. The SE values of the obtained composites were standardized per 20 mm of the composite width, and then per mm for better comparison.

Table 1: Simulation Results of SE for HDPE-Aluminum Nanoparticle Composites

Freq (GHz)	Pi (W/m²)	Po (W/m²)	Pi/Po	log Pi/Po	SE per 20 mm (dB)	SE per mm (dB)
8	5.76E-29	1.37E-27	4.20E-02	1.3767	-13.7675	-0.6883
8.5	5.03E-29	2.94E-27	1.71E-02	5.1979	-51.9793	-2.5989
9	6.26E-28	1.98E-27	3.16E-01	0.5003	-5.0034	-0.2501
9.5	6.84E-28	5.16E-28	1.32E+00	-0.1220	1.2202	0.0610
10	7.80E-29	2.78E-25	2.80E-04	4.1827	-41.8278	-2.0913
10.5	8.92E-27	1.44E-28	6.19E+01	-1.7917	17.9172	0.8958
11	6.26E-28	5.15E-28	1.22E+00	-0.0850	0.8505	0.0425
11.5	1.43E-27	9.60E-29	1.49E+01	-1.1744	11.7444	0.5872
12	6.58E-26	3.00E-28	2.19E+02	-2.3406	23.4069	1.1703

3.1. SE Analysis at Different Frequencies

Low Frequencies (8–9 GHz):

For the lower frequencies, the SE values are negative, which implies poor shielding performance since energy is easily transmitted. For instance, the SE at 8 GHz equals to -13.77 dB which points to dominant reflection losses and relatively low absorption. The nanoparticles appear to be least efficient in the case of absorbing or lessening the strength of electromagnetic waves at this range.

Mid-range Frequencies (9. 5–10. 5 GHz):

In the mid frequencies there is a general increase in the SE values, where the SE at 9.5GHz becomes positive i.e. 1.22dB. It points to the fact that absorption and scattering mechanisms are getting more effective. By 10.5 GHz, the SE improves to 17. 91 dB, it can be noticed considerable energy loss due to subsequent reflections and scattering in the nanoparticle matrix.

High Frequencies (11–12 GHz):

At the higher frequencies, the SE values rise significantly, and the SE is attained to 23.40 dB has been measured at 12 GHz. It was observed that shielding becomes more effective at increasing frequency from factors such as absorption, reflection as well as scattering effects. The higher frequency increases the chances of nanoparticles to interact with the electromagnetic waves hence less transmission and a better shielding efficiency.

3.2. Electric Field and Power Flow Analysis at 12 GHz

The results at 12 GHz assist in revealing the electric field distribution and the power outflow of the generated electromagnetic waves which are useful in analyzing the interaction of the electromagnetic waves with the composite.

3.2.1. Electric Field Distribution

Fig. 1 shows the x-component, y-component, z-component, and norm of the electric fields at 12 GHz for the HDPE-Al nanoparticle composite. The electric field norm (E_{norm}) describes the behavior of the electromagnetic wave with the composite material, with higher field concentration at the surface of the nanoparticles. The distribution reveals that the majority of the field is localized in specific regions; therefore, there is a significant scattering effect at this frequency.

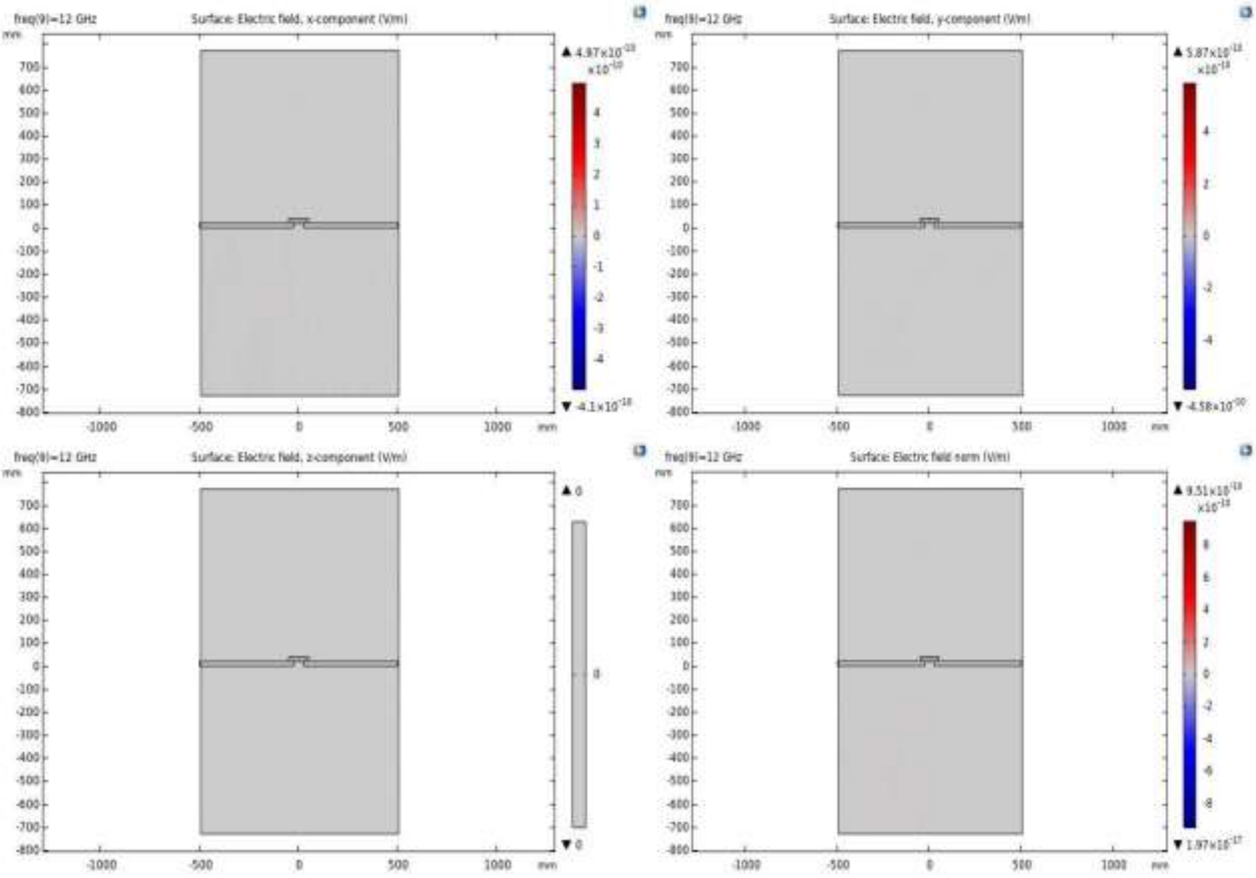

Figure-2: Electric Field at 12 GHz with HDPE + Al Nanoparticles

3.2.2. Power Outflow Analysis

As shown in Figure 2, this is the time-averaged power flow components and the total power outflow at 12 GHz. The power outflow reveals an extremely low signal of leakage from the composite, which is nearly equal to zero in most areas, thus confirming substantial EMI shielding performance at this frequency. This is due to the surface resonances from the aluminum nanoparticles where the power flow in some select areas is high.

These graphs clearly show the shielding effectiveness of the composite against electromagnetic wave modulation at high frequencies thus aluminum nanoparticle composites are suitable for high frequency EMI shield applications.

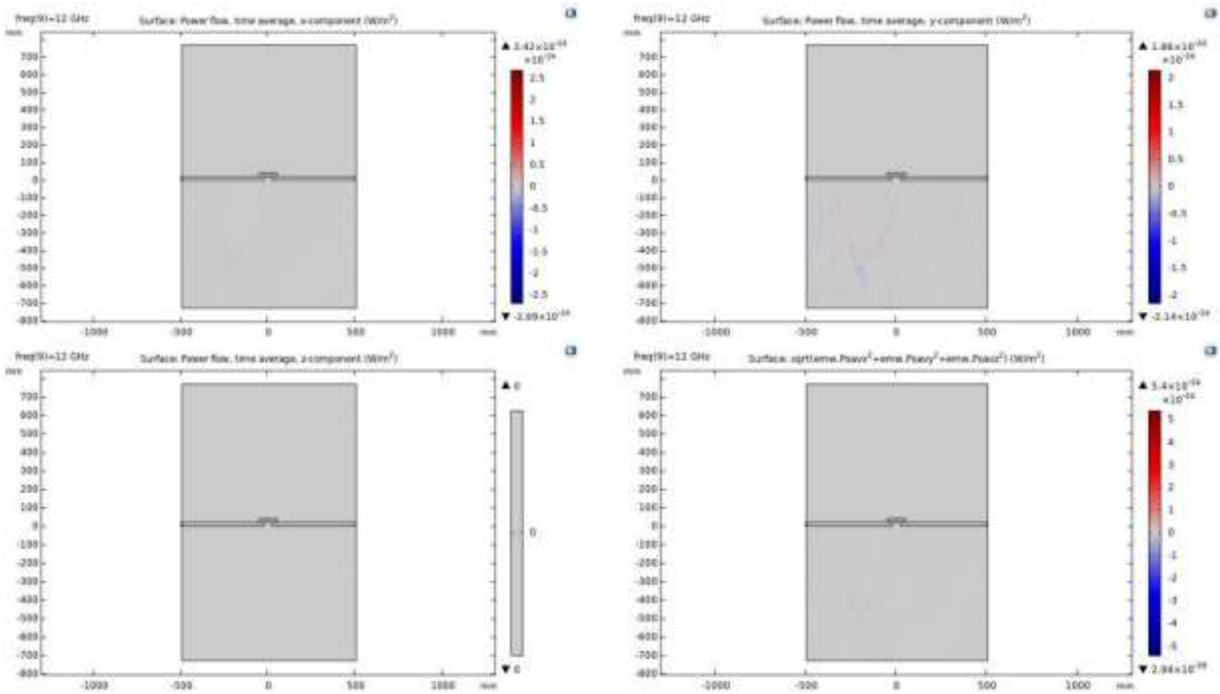

Figure-2: Power Flow at 12 GHz with HDPE + Al Nanoparticles

3.3. SE Vs Frequency Plot

However, to facilitate the understanding of the performance of SE over the frequency band, a plot of SE with frequency is shown below. A trend is observed where SE rises with frequency to attain their maximum at 12 GHz. This trend is in agreement with literature evidence which recommends smaller particle sizes and larger surface areas as shielding is enhanced as the frequency increases.

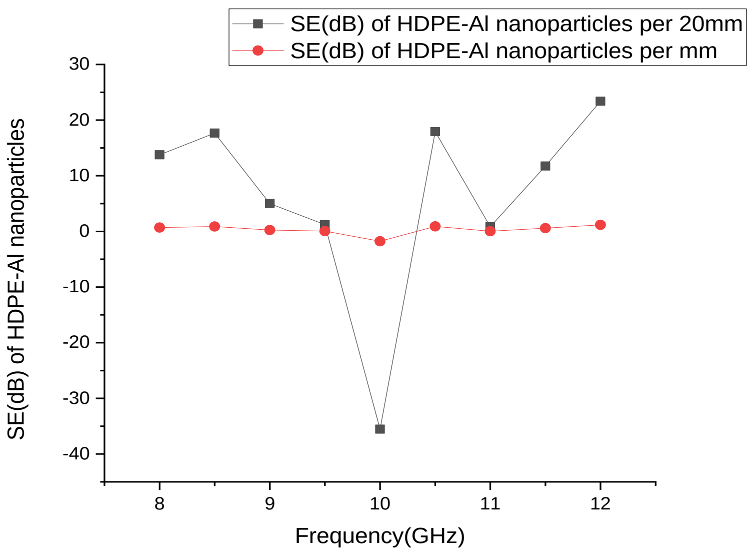

Figure-3: SE vs. Frequency Plot

4. Conclusion

This research aimed at assessing the shielding effectiveness (SE) of high-density polyethylene (HDPE) composites filled with aluminum nanoparticles through computational modeling and simulation in COMSOL Multiphysics™. From these analyses, it was evident that the composite material offered protection from EMI at higher frequencies which was at around 12GHz with the SE recorded as 23.41 dB. Yet, resonant effects were identified at 10

GHz, which resulted in a lower SE. This present study may thus form a basis for future studies aimed at enhancing the application of composite materials in the specific frequency ranges and enhancing the shielding functionality.

Further works will comprise of investigating the impact of different particle size and concentration towards the improvement of the materials EMI shielding ability. Furthermore, further experimental studies will be performed to support simulation and to focus on the new types of composites for EMI shielding in practice.

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