UDC 537.874.6

ELECTRODYNAMIC ANALYSIS OF NANOCOMPOSITE MICROWAVE SCREENING VIA EQUIVALENT *RLC* CIRCUIT MODELS

Y. Wu, S.L. Prischepa
Educational Institution "Belarusian State University of Informatics and Radioelectronics", Minsk, Republic of Belarus

Abstract. This study presents an electrodynamic analysis of hybrid nanocomposites consisting of carbon nanotubes (CNTs) with embedded ferromagnetic nanoparticles for microwave screening. By utilizing equivalent parallel and series *RLC* circuit models, we demonstrate that these materials offer a unique combination of broadband shielding and tunable resonance. Experimental parameters for resistance (*R*), capacitance (*C*), and inductance (*L*) were mapped to the physical morphology of the nanocomposite, revealing that the integration of magnetic nanoparticles significantly enhances the inductive response and absorption characteristics. Results indicate that while parallel networks provide stable broadband attenuation, series configurations enable frequency-selective screening, making these hybrids ideal for high-frequency applications in 5G/6G and aerospace sectors.

Keywords: resistance; capacitance; inductance; carbon nanotubes; ferromagnetic nanoparticles; series circuit; fully parallel circuit; impedance; screening efficiency; *RLC* circuit.

Introduction

The rise of high-frequency electronics has turned the electromagnetic (EM) spectrum into a crowded space. To keep electronic "noise" from degrading sensitive devices, nanocomposites are widely used nowadays. Among these, polymer-based nanocomposites reinforced with conductive fillers like carbon nanotubes (CNTs) with embedded Fe nanoparticles [1] have emerged as frontrunners [2]. While full-wave numerical simulations provide high accuracy, equivalent *RLC* circuit modeling offers a computationally efficient alternative, providing deep physical insight into the interaction between microwave radiation and the microscopic morphology of the composite. Moreover, treating a nanocomposite as an equivalent series or parallel *RLC* (resistor–inductor–capacitor) circuit allows predicting its shielding effectiveness (SE) without detailed quantum-level analysis [3].

In a nanocomposite, the electromagnetic response is governed by three primary phenomena:

1. Ohmic Loss (*R*): The movement of charge carriers through the conductive filler network.
2. Polarization and Capacitive Storage (*C*): The accumulation of charge at the interfaces between conductive fillers and the insulating polymer matrix (Maxwell-Wagner-Sillars effect).
3. Self-Inductance (*L*): The magnetic energy stored due to the current loops and the intrinsic magnetic properties of embedded ferromagnetic nanoparticles.

Model Simulation

We consider two types of *RLC* circuits: series and parallel. In a series configuration, the components are arranged in a single path. This model is often used to describe nanocomposites in which the conductive fillers are sparse (below the percolation threshold) or in which the material behaves like a thin, capacitive barrier. The total impedance (Z_s) of a series *RLC* circuit is given by

$$Z_s = R + j\omega L + \frac{1}{j\omega C}, \tag{1}$$

where $\omega = 2\pi f$ is the angular frequency. At the resonance frequency ($f_0 = \frac{1}{2\pi\sqrt{LC}}$), the inductive and capacitive reactances cancel each other out.

At low frequency, the capacitor dominates ($1/j\omega C$ is large), leading to high impedance and high reflection. At resonance, impedance is at its minimum (equal to *R*). This is often where the material is most "transparent" or where absorption peaks depend on the matching to free space (377 Ohm). Finally, at high frequency, the inductor dominates ($j\omega L$), causing the shielding effectiveness to rise again as the material resists changes in current.

The fully parallel *RLC* circuit is the preferred model for nanocomposites that have reached the percolation threshold. Then the fillers form continuous conductive networks that allow for "bulk" current flow. The equivalent impedance (Z_p) is then

$$Z_p = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\omega C - \frac{1}{\omega L}\right)^2}} \tag{2}$$

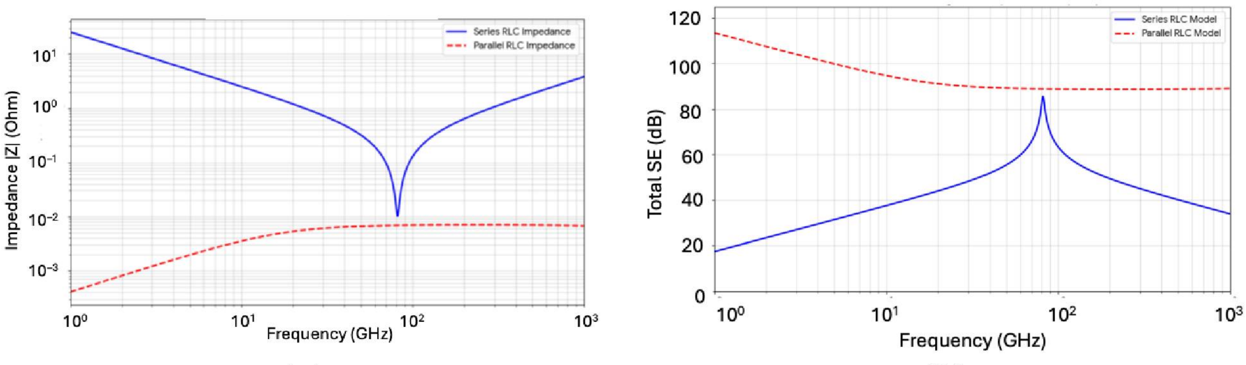
It follows from Eq. (2) that because the components are in parallel, the branch with the lowest impedance dictates the behavior. If *R* is very low (high conductivity), the material acts as a highly reflective "Faraday Cage." At the frequency where $\omega C = 1/\omega L$, the impedance Z_p reaches its maximum. This can be strategically tuned to create "band-stop" filters where the material selectively blocks or allows specific microwave frequencies. Finally, it should be noted that parallel circuits generally provide a more accurate representation of the wideband shielding seen in dense carbon-based composites.

Based on the above considerations and on the approach of the evaluation of the permittivity and permeability of a CNT-based nanocomposite filled with Fe nanoparticles [2,4], it is possible to estimate the screening efficiency (*SE*), which refers to the ability of the nanocomposite to attenuate EM interference or to shield internal electric fields from external influence. In an *RLC* network representing a nanocomposite, the screening efficiency is a measure of the ratio between the incident power (P_I) and the transmitted power (P_T), $SE = 10\log_{10}\left(\frac{P_I}{P_T}\right)$. In the *RLC* framework, this power loss is determined by three physical mechanisms: Reflection (*Re*), Absorption (*A*), and Multiple Reflections (*M*). Then the total screening efficiency is the sum of these three components,

$$SE_{Total} = SE_{Re} + SE_A + SE_M \tag{3}$$

All the components of the Eq. (3) can be calculated considering real parameters of the *RLC* circuit. In this work, we employ the following characteristic parameters: *R*=0.003–0.015 (0.002–0.01) Ohm, *C*=1–15 (1–10) pF, and *L*=0.22–1.8 (0.01–0.1) pH for series (parallel) circuit, which are typical for CNT-based nanocomposites [3,4].

The results of the calculated impedance and total *SE* versus frequency for both parallel and series configurations for a fixed parameter values from the above intervals are presented in Figures 1a and 1b, respectively.



(*a*) (*b*)

a – Magnitude of impedance |*Z*| versus frequency; (*b*) – Microwave screening efficiency (*SE*) versus frequency

The resonance frequency determines the "tuning" of the material – the specific frequency at which the material's inductive and capacitive behaviors balance each other out. It was obtained that, for series *RLC* circuit, using given ranges of the parameters, the resonance frequency falls within the 29.06 to 251.65 GHz range. This makes the series-mode nanocomposite highly relevant for 5G/6G communication bands and millimiter-wave radar shielding. For parallel *RLC* model, the resonance shifts significantly hugher, spanning 129.95 GHz to 1.59 THz. This, in turn, indicates that the parallel-coupled network is better suited for sub-terahetrtz and teraherts applications. At the midpoint resonance, the impedance drops to its minimum value (the ohmic resistance). Because *Z* becomes small (10^{-2} Ohm), the material acts as a near-perfect conductor at this frequency. This results in a sharp spike in *SE*, reaching over 80 dB. Away from resonance, the *SE* drops as the capacitive reactance (at low frequencies) or inductive reactance (at high frequencies) increases the total impedance, allowing more EM energy to pass through.

The parallel configuration represents a well-percolated network where conductive pathways are abundant. Unlike the series model, the parallel circuit maintains an extremely low impedance (between 10^{-4} and 10^{-2} Ohm) across almost the entire microwave and millimeter-wave spectrum. Because the total impedance remains consistently much lower than the impedance of free space, the *SE* is exceptionally high and stable, maintaining values above 90 dB. The "anti-resonance" (where impedance would peak) occurs much higher in the THz range, meaning that for standard microwave applications, this material acts as a consistent, high-performance shield.

Conclusion

The synergy between CNT and high-permeability Fe nanoparticles creates a material that transcends the limitations of single-component shields. While CNTs provide the baseline conductivity for reflection, the magnetic inclusions enable tunable absorption and superior impedance matching. By adjusting the *RLC* parameters – specifically the inductance through nanoparticle loading and capacitance through polymer spacing – it is possible to design "smart" shields. These nanocomposites are uniquely positioned to meet the rigorous demands of next-generation telecommunications and aerospace applications, where lightweight, broadband, and tunable EMI protection is paramount.

The obtained results demonstrate that, if CNT-based nanocomposite is synthesized such that fillers act in series (e.g., layered or aligned structures), it can be used as a frequency-selective surface. It will provide maximum protection at a specific band while being relatively more transparent at lower frequencies. If, vice versa, the material is synthesized to form a dense, isotropic 3D network (above the percolation threshold), it will serve as a superior broadband shield. It is ideal for military or high-precision laboratory environments where total suppression of signals from 1 GHz to 1 THz is required.

References

1. Danilyuk A.L., Komissarov I.V., Labunov V.A., Le Normand F., Derory A., Hernandez J.M., et al. (2015) Manifestation of Coherent Magnetic Anisotropy in a Carbon Nanotube Matrix with Low Ferromagnetic Nanoparticle Content. *New Journal of Physics*. 17(2), 023073.

2. Gupta S., Tai N. (2019) Carbon Materials and their Composites for Electromagnetic Interference Shielding Effectiveness in X-band. *Carbon*. 152, 159–187.

3. Atdayev A., Danilyuk A. L., Prischepa S. L. (2015) Interaction of Electromagnetic Radiation in the 20–200 GHz Frequency Range with Arrays of Carbon Nanotubes with Ferromagnetic Nanoparticles. *Beilstein Journal of Nanotechnology*. 6, 1056–1064.

4. Labunov V. A., Danilyuk A. L., Prudnikava A. L., Komissarov I., Shulitski B. G., Speisser C., et al. (2012) Microwave Absorption in Nanocomposite Material of Magnetically Functionalized Carbon Nanotubes. *Journal of Applied Physics*. 112 (2), 024302.

Information about the authors

Wu Y., master student, Department of Information Security, Educational Institution "Belarusian State University of Informatics and Radioelectronics", ilmsiaoms@gmail.com.

Prischepa S.L., Dr. of Sci. (Phys. and Math.), Professor, Professor at the Department of Information Security, Educational Institution "Belarusian State University of Informatics and Radioelectronics", prischepa@bsuir.by.