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Research Article

Investigation of Electromagnetic Wave Propagation in Triple Walled Carbon Nanotubes

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Abstract:

In this study, behaviors of electromagnetic wave propagation in a unique and complex three-walled carbon nanotube structure are investigated. The investigated structure is formed by nesting three distinct nanotubes, and the interactions between them are thoroughly analyzed, taking into account their varying electromagnetic, material, and nano properties. The structure is designed at a nanoscale to provide a comprehensive description of electromagnetic (EM) wave propagation, including the electromagnetic interaction between the second nanotube, located in the middle of the structure, and the other two nanotubes situated in both the inner and outer portions of the structure. The inner and outer tubes of the triple-walled carbon nanotube (TWCNT) interact, resulting in high interaction parameters ($\gamma: 5 \times 10^{17}$). The dispersion relation shows the relationship between the wavevector (k) and the angular frequency (ω) of waves propagating through the nanotube. In this case, the dispersion relation shows that the second and third frequencies are obtained at high values, while there is no significant difference in the fundamental frequency values of the TWCNT. This suggests that the interaction between the inner and outer tubes of the TWCNT has a greater effect on the higher frequency modes. The high interaction parameters indicate that the TWCNT has a strong intertube interaction, which can have important implications for its properties and potential applications.

1. Introduction

The discovery of carbon nanotubes has had a profound impact on the field of nanomaterials, opening a multitude of possibilities for researchers to explore [1]. This has resulted in extensive studies of nanoscale structures and devices that utilize these materials, as well as optical structures that have greatly benefited from these developments [2-4]. Researchers have conducted significant research on metamaterials and photonic structures based on electromagnetic principles [5-8].

Electromagnetic (EM) wave shielding, commonly known as stealth technology, is another crucial area of study based on the principles of electromagnetics [9-11]. Typically, carbon nanotube-based structures are used to absorb radar beams in the shielding process, with the permittivity and permeability of carbon nanotubes being utilized to provide an effective method of protecting against electromagnetic waves.

Nanotubes are classified as single-walled (SWCNT) and multi-walled (MWCNT), and both have been extensively studied using theoretical and experimental methods [12-15]. A theoretical study on the electromagnetic wave propagation behavior in a double-walled carbon nanotube (DWCNT) was presented in [15].

The present study focuses on the electromagnetic wave propagation behavior of the MWCNT structure consisting of three walls (TWCNT), which is a topic of great interest. The interaction between the walls and the effects of changes in material parameters on the electromagnetic wave propagation are investigated, as well as the interaction between the innermost and outermost carbon nanotubes of the TWCNT structure. This study is unique in that it examines a three-walled structure in which all walls interact with each other. The aim of this study is to fill a gap in the literature on this subject, providing a valuable contribution to the field.

2. Material and Methods

To examine the behavior of electromagnetic waves within a particular structure, it is essential to derive the propagation equation for single-walled carbon nanotubes (SWCNTs) in one dimension (1D). The propagation equation is a key factor in understanding the nature of wave propagation in SWCNTs and designing electronic devices such as waveguides, filters, and other related technologies.
Maxwell's equations, which describe the behaviour of electromagnetic waves, can be expressed in the following manner [16] under the assumptions of a linear, isotropic, and homogeneous region that is free of sources:

$$\nabla \times \vec{E} = -i\omega\mu\vec{H} \qquad (1)$$

$$\nabla \times \vec{H} = i\omega\varepsilon\vec{E} \qquad (2)$$

Here, E refers to the electric field, H denotes the magnetic field, ε stands for electric permittivity, and μ denotes magnetic permeability.
By solving these equations and applying boundary conditions, we can derive the propagation equation for electromagnetic waves in 1D SWCNTs. The importance of this equation cannot be overstated in the field of nanoelectronics and optoelectronics. Its applications include the design of high-speed transistors, photodetectors, and solar cells.
Fig. 1 illustrates a single tube with three distinct layers of walls. The first wall is the outermost layer, followed by the middle layer, and the third wall is the innermost layer. Meanwhile, Fig. 2 shows a cross-sectional view of the same tube with its three walls.
Upon solving Equations (1) and (2), a partial differential equation governing the propagation of electromagnetic waves as a function of both time and space coordinates is obtained. The equation is presented below:

$$\frac{1}{\mu\varepsilon}\frac{\partial^2 H_x}{\partial x^2} - \frac{\partial^2 H_x}{\partial t^2} = 0 \qquad (3)$$

Here H_x represents the magnetic field vector component along the x-axis.

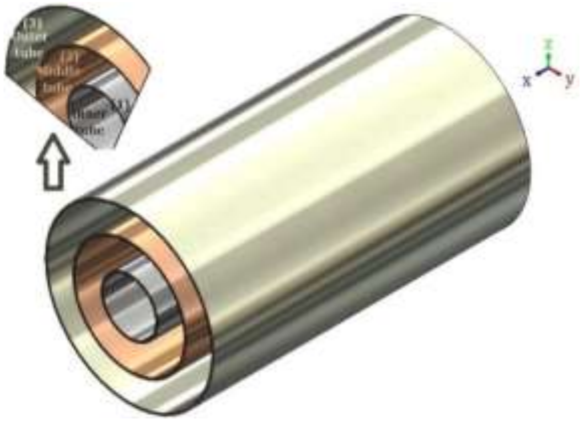

Figure 1. *A single tube with three walls.*

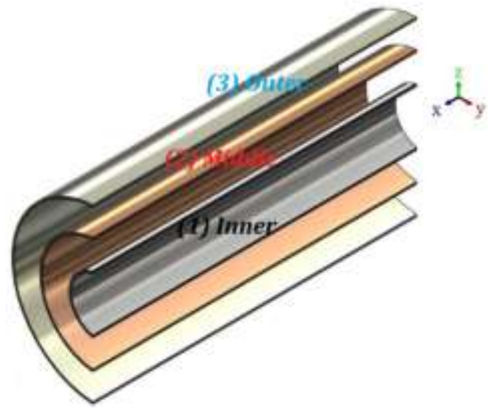

Figure 2. *A cross-sectional view of the tube with three walls.*

The nonlocal theory proposes that the material property parameters (μ, ε) of any given point on a carbon nanotube, which serves as the reference point, influence the material property parameters (μ, ε) of all the adjacent local points. Additionally, the material property parameters (μ, ε) of the reference point also impact the material property parameters (μ, ε) of all the nonlocal points that are not adjacent to the reference point. As a result, the electromagnetic wave equation of a single-walled carbon nanotube (SWCNT) can be expressed in a particular form as in the following form [13-15]:

$$Q\frac{\partial^2 H_x}{\partial x^2} = \left[1 - \eta^2\frac{\partial^2}{\partial x^2}\right]\frac{\partial^2 H_x}{\partial t^2} \qquad (4)$$

Here, $Q=1/(\mu\varepsilon)$ represents material parameter, η represents the nonlocal coefficient.

The study employs a thorough evaluation approach that involves utilizing a specific set of material parameters [12]. These parameters, which are denoted by Q values, have been carefully selected from a range of 0.02 to 0.1. In Fig. 3, a triple-walled carbon nanotube is illustrated in a comprehensive manner, showcasing the intricate interplay between each individual tube. The image provides a detailed depiction of the internal structure of the nanotube, highlighting the complex interactions that occur between the different layers.

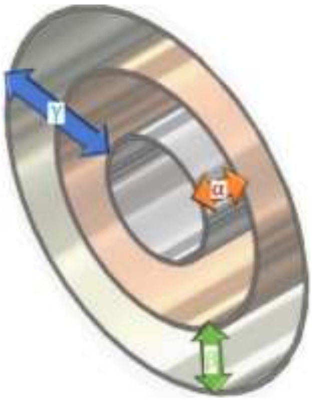

Figure 3. *Electromagnetic interactions between the tubes within the three-walled carbon nanotube, namely α, β, and γ.*

Electromagnetic interactions, namely α, β, and γ, are observed between the tubes within the three-walled carbon nanotube. The phenomenon can be attributed to the nanotube's unique structural arrangement, which enables the tubes to influence each other electromagnetically. In view of all the information available, the equations governing the propagation of electromagnetic waves in the triple-walled carbon nanotube (TWCNT) with complete interaction among the walls (α, β, and γ) are presented below:

$$Q_n \frac{\partial^2 H_n}{\partial x^2} = \left(1 - \eta^2 \frac{\partial^2}{\partial x^2}\right) \frac{\partial^2 H_n}{\partial t^2} - \lambda_n (H_n - H_{n+1}) \qquad (5)$$

Here, n and m are the tube index, $\lambda_n\!: \alpha \ or\ \beta$ indicates the interaction between adjacent tubes, while in Equ. (6), γ indicates the interaction in non-adjacent tubes:

$$Q_m \frac{\partial^2 H_m}{\partial x^2} = \left(1 - \eta^2 \frac{\partial^2}{\partial x^2}\right) \frac{\partial^2 H_m}{\partial t^2} - \gamma (H_m - H_n) \qquad (6)$$

The displacement of an electromagnetic wave, denoted by $H(x, t)$, can be expressed as follows:

$$H(x,t) = h e^{\mathrm{i}(\omega t - kx)} \qquad (7)$$

Here, Equ. (7) contains three variables, with 'h' representing the traveling wave, 'ω' denoting the frequency of electromagnetic wave propagation, and 'k' representing the wave number. By substituting Equ. (7) into Equations (6) and (5), electromagnetic wave dispersion relations (k - ω) of the three tubes can be determined. This process is crucial in comprehending how the wave properties relate to the medium in which it moves. The dispersion relation (k - ω) is particularly important in electromagnetism, as it enables us to predict the behavior of electromagnetic waves in various media.

3. Results and Discussions

This section delves into the propagation of electromagnetic waves in three different cases, each with unique parameters and properties.

In the first case, the parameter related to the electromagnetic properties of the middle tube is set to be the strongest. This scenario is particularly interesting because it highlights the impact of the middle tube, which may have a significant influence on the overall behavior of the electromagnetic wave.

In the second case, the parameter related to the electromagnetic properties is equal in each of the three tubes. This makes for a more balanced and uniform distribution of electromagnetic properties, which can be useful in certain applications.

In the third case, the interaction parameter (β) between the middle and outer tube is twice as large as the other interaction parameters. This creates a more complex and intricate system, where the interaction between the tubes is not equally distributed. Fig. 4 displays all the values of the three tubes, which are selected to be equal. This offers an opportunity to compare the different cases and observe the differences and similarities between them.

Furthermore, the investigations whose results are given in Fig. 5 and Fig. 6 were conducted specifically for carbon nanotubes, which represent a nonlocal situation. This is an important consideration as it affects the behavior of the electromagnetic waves and may have implications for various applications.

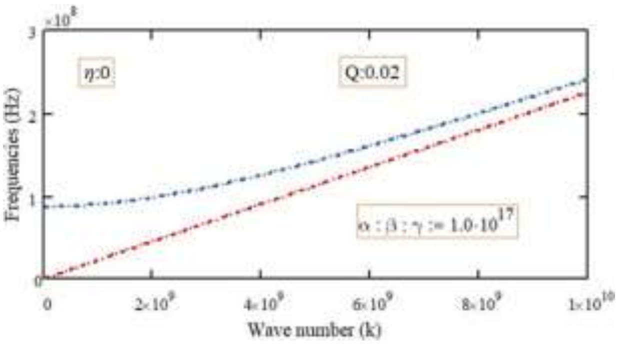

Figure 4. *The dispersion relation of an EM wave in a three-walled tube with equal interactions.*

Since all values are chosen equal in Fig. 4, the structure behaves like a double-walled tube, and the electromagnetic frequency values are obtained coincidently, as expected.

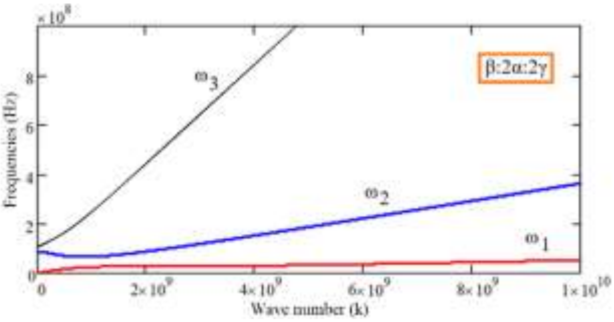

Figure 5. *Curves of dispersion relation for EM waves in carbon nanotubes with varying interactions.*

The graph depicted in Fig. 5 reveals that the 3rd frequency values are significantly higher than the other frequency values. This is primarily due to the fact that the interaction between the outer and middle tubes is high, which results in an amplification of the 3rd frequency values. Therefore, it can be inferred that the outer and middle tubes have a strong influence on the overall frequency response. The examinations conducted to obtain Fig. 6 differed from those used for Fig. 5 in that material parameter values were selected independently for each of the three tubes. The calculations were performed with a focus on the variation of the material parameter of the inner tube, resulting in the determination of the frequencies of electromagnetic wave propagation and dispersion curves. It is evident from Fig. 6 that only high material parameter values of the inner tube lead to low electromagnetic frequency values.

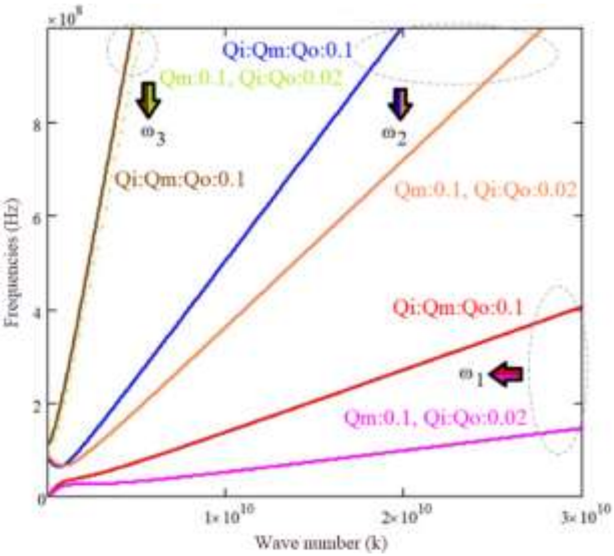

Figure 6. *The dispersion relation curves of EM waves in carbon nanotubes with varying material parameters.*

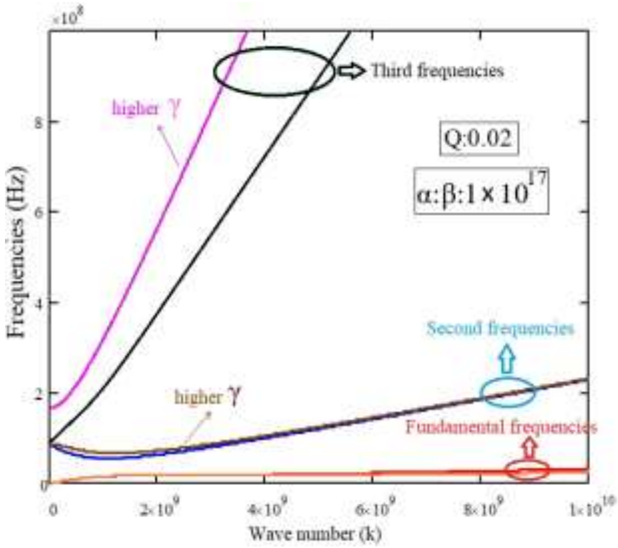

Figure 7. *EM wave dispersion relation curves in carbon nanotubes with varying interaction parameters.*

The dispersion relation (k - ω) of a three-walled carbon nanotube (TWCNT) with η>0 and η:1 is presented in Fig. 7. The inner and outer tubes of the triple-walled carbon nanotube (TWCNT) interact with each other, resulting in high interaction parameters ($\gamma: 5 \text{ x } 10^{17}$). The dispersion relation shows the relationship between the wavevector (k) and the angular frequency (ω) of waves propagating through the nanotube. In this case, the dispersion relation shows that the second and third frequencies are obtained at high values, while there is no significant difference in the fundamental frequency values of the TWCNT. This suggests that the interaction between the inner and outer tubes of the TWCNT has a greater effect on the higher frequency modes. The high interaction parameters indicate that the TWCNT has a strong intertube interaction, which can have important implications for its properties and potential applications.

4. Conclusions

Our study aimed to investigate the propagation of electromagnetic waves in a carbon nanotube with three walls, known as a three-walled carbon nanotube (TWCNT), and to explore the interaction between the inner and outer nanotubes while taking into account the assumption that all three tubes affect each other. This particular aspect had not been adequately explored in previous studies, and thus, our research makes a significant contribution to filling a gap in the literature on the subject.

To achieve our research objectives, we applied Eringen's nonlocal theory, which is a mathematical model used to describe the behavior of small-scale materials. Our analysis of the TWCNT structure revealed that adjusting the electromagnetic wave propagation frequencies is possible by changing the interaction in the tubes, material parameters, and nonlocal constants. This finding holds significant potential for future research in this field.

We also found that the material parameters of the structures in which wave propagation occurs impact the electromagnetic wave propagation frequencies, specifically with regard to the tubes to which the material belongs. This means that an increase in EM wave propagation frequencies is observed as the material parameter increases.Moreover, our research stands out among earlier studies [8, 15] in terms of logic because it highlights several crucial issues, including the impact of tube interaction on all three tubes (γ). We carefully analyzed the structure to conclude that our investigation method can be applied in future studies to investigate wave propagation in two-dimensional, multilayer nanoplates, offering the potential to gain deeper insights into the behavior of small-scale materials.Overall, our study provides a comprehensive investigation into the propagation of electromagnetic waves in TWCNTs, presenting valuable insights into the interaction between the inner and outer nanotubes and their impact on all three tubes. Our findings have significant implications for future research, particularly in adjusting the electromagnetic wave propagation frequencies.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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