Electromagnetic wave propagation behavior of conjoined carbon nanotubes

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This study investigates the electromagnetic wave propagation behavior of a structure consisting of two parts with different material parameters. Investigations are made with the carbon nanotube approach. Therefore, this nanostructure's electromagnetic wave propagation behavior analyses are made at the macro (local) and nano (nonlocal) levels. Nonlocal properties of the related nanostructure and Maxwell's equations are used in the investigations. The electromagnetic wave propagation behavior of the structure is determined by changing parameters such as material parameters and nonlocal effects in the nanostructure. While the D1/D2 ratio of the material parameters of the nanostructure is constant, the electromagnetic wave propagation frequency values of Joint I and Joint II in the structure decrease steadily with the increase of the nonlocal constant.

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1. Introduction

In recent decades, rapid advances in the fields of electromagnetic and optics have increased the interest in photonic and phononic structures [1-7]. Although electromagnetic wave propagation behaviors in photonic and phononic structures are similar in principle, the basis of this behavior is based on wave propagation equations. Moreover, Maxwell's equations investigate electromagnetic wave propagation behavior in photonic structures [8-11]. Numerous researchers have shown interest in electromagnetic theory-based applications [12, 13] focusing on switching. One notable study [14] examines frequency values of electromagnetic wave propagation within a structure possessing non-homogeneous material properties. Studies [15-17] explore the properties of microwaves and waveguides in detail by combining optical structures with varying material properties to form photonic crystal structures. Research studies conducted in [18-20] have focused on exploring how changes in material parameters affect the behavior of electromagnetic wave propagation in waveguides and their layers.

Similarly, investigations in [21, 22] have examined how structures' electromagnetic wave propagation behavior is influenced by material property parameters (μ, ε). Additionally, studies in [23-26] have examined structures' transmission and reflection parameters concerning changes in material property parameters (μ, ε). In a four-part waveguide, a comprehensive study has been conducted on the formation of waveforms during electromagnetic wave propagation [27]. Waveform characteristics determine the behavior of electromagnetic wave propagation. To comprehend the formation of waveforms, it is crucial to have a clear understanding of transmission and reflection concepts. In-depth analysis of electromagnetic wave propagation involves examining transmission and reflection states, as seen in sources such as [28-32]. Another area of focus in recent years has been the absorption of electromagnetic waves. Applying electromagnetic wave transmission principles, absorption in carbon nanotube structures has been observed [33-35].

This article discusses Eringen's nonlocal theory and its significance. The nonlocal theory allows for comparing results obtained by the atomic simulation method, making it essential. The results obtained using the nonlocal theory are compared with the atomic simulation method, and it is observed that the nonlocal theory yields more satisfactory results [36]. According to the nonlocal theory, two non-adjacent atoms can impact each other [37, 38]. Therefore, the nonlocal theory is an ideal method to study electromagnetic wave propagation in carbon nanotubes. Studies have been conducted to investigate the nonlocal effects of carbon nanotubes on electromagnetic wave propagation. The impact on electromagnetic wave propagation in both local and nonlocal states of carbon nanotubes has been emphasized through extensive research [39-42]. Electromagnetic wave propagation has been closely examined in double-walled carbon nanotubes, where interaction between the inner and outer tubes was observed [42]. Other studies have focused on the dispersion properties of electromagnetic waves in carbon nanotubes and their velocities [43-45].

This article investigates the propagation of electromagnetic waves in carbon nanotubes consisting of two distinct nanostructures. The study delves into the impact of changes in material property parameters (μ, ε) and nonlocal effects on the frequencies of electromagnetic wave propagation. It also examines these waves' transmission and reflection properties and analyzes the resulting electromagnetic waveforms.

2. Theoretical analysis

An examination is conducted on how electromagnetic waves behave in a combined structure, as depicted in Figure 1. The structure has two joints with varying material property parameters, μ and ε. Electromagnetic waves propagate without loss in both Joint I and Joint II. However, the wave's characteristics, such as amplitude and frequency, are altered during the transition from Joint I to Joint II.

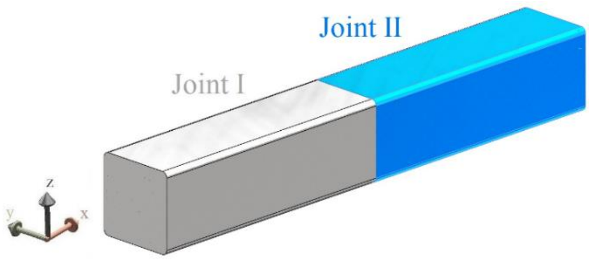

Fig. 1. Geometry for defining the electromagnetic (EM) wave propagation behavior of the investigated conjoined structure (color online)

In a source-free, linear isotropic, and homogenous region, Maxwell's equations are [11]:

$$\nabla x\vec{E} = -i\omega\mu\vec{H} \quad (1a)$$

$$\nabla x\vec{H} = i\omega\varepsilon\vec{E} \quad (1b)$$

where $i = \sqrt{-1}$, μ is permeability, ε is permittivity, E is the electrical field (axis y), and H is the magnetic field (axis x) (axis z). The 3-dimensional wave equation given as Equ. 2 is obtained using Maxwell equations given in Equ. (1a) and Equ. (1b).

$$\nabla \times (\nabla \times \vec{H}) = \nabla(\nabla \cdot \vec{H}) - \nabla^2\vec{H} = \nabla \times \left(-\mu\frac{\partial \vec{H}}{\partial t}\right) = 0 \quad (2)$$

By solving Equ. 2, the partial differential equation of 1-D EM wave propagation concerning time and space is obtained as follows:

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

According to the nonlocal theory, the material properties (μ, ε) of a specific point on a nanotube impact the material properties (μ, ε) of all nearby points. As a result, the electromagnetic wave equation of an individual, unconnected nanotube can be expressed as shown below [37, 38]:

$$D\frac{\partial^2 H_x}{\partial x^2} = \left[1 - (e_0 a)^2\frac{\partial^2}{\partial x^2}\right]\frac{\partial^2 H_x}{\partial t^2} \quad (4)$$

where $D=1/(\mu\varepsilon)$ represents the material parameter, with "a" serving as an internal characteristic length and "e_0" is a constant. The nonlocal coefficient is denoted by $e_0 a{:}\, n$. The wave propagation field of the investigated structure is represented by $u(x,t)$. Accordingly, the material parameter:

$$D_m = \frac{1}{\mu_m\varepsilon_m}, \quad m{:}\,1 \text{ (Joint I)}, m{:}\,2 \text{ (Joint II)} \quad (5)$$

is obtained. It should be noted that "*m:1*" refers to Joint 1 and "*m:2*" refers to Joint II.

$$u_1(x,t) = U_1 e^{i(\omega t - \mathrm{k}_1 x)} + U_1 e^{i(\omega t + \mathrm{k}_1 x)} \quad (6a)$$

$$u_2(x,t) = U_2 e^{i(\omega t - \mathrm{k}_2 x)} \quad (6b)$$

where $U_{1rf}{:}\, U_1 e^{i(\omega t + \mathrm{k}_1 x)}$ indicates the reflected EM wave of Joint I, $U_{1in}{:}\, U_1 e^{i(\omega t - \mathrm{k}_1 x)}$ denotes the incident EM wave of Joint I, and $U_{2tr}{:}\, U_2 e^{i(\omega t - \mathrm{k}_2 x)}$ signifies the transmitted EM wave of joint II. Also, ω represents the frequencies of electromagnetic wave propagation, while k_1 and k_2 refer to the wavenumbers in Joint I and Joint II, respectively. The determination of wavenumbers k is carried out using Equ. (7).

$$\mathrm{k}_{m+1} = \mathrm{k}_m\sqrt{\frac{D_{m+1}}{D_m}} \quad (7)$$

By substituting Equ.s (6a, 6b) into Equ. (4), electromagnetic wave propagation frequencies for Joint I and Joint II can be determined. Equ. (8a) provides the EM wave propagation frequencies for Joint I as ω_1, while Equ. (8b) gives the EM wave propagation frequencies for Joint II as ω_2.

$$\omega_1 = \sqrt{\frac{D_1 \mathrm{k}_1{}^2}{1 + n_1{}^2 \mathrm{k}_1{}^2}} \quad (8a)$$

$$\omega_2 = \sqrt{\frac{D_2 \mathrm{k}_2{}^2}{1 + n_2{}^2 \mathrm{k}_2{}^2}} \quad (8b)$$

By equalizing Equ.s (8a, 8b), the relation $n_2 = n_1\sqrt{\frac{D_2}{D_1}}$ can be derived. This leads to the $\omega_1 = \omega_2$ relation, which indicates that EM wave propagation frequencies related to Joint I and Joint II are equal. The traveling electromagnetic wave is depicted in Fig. 2.

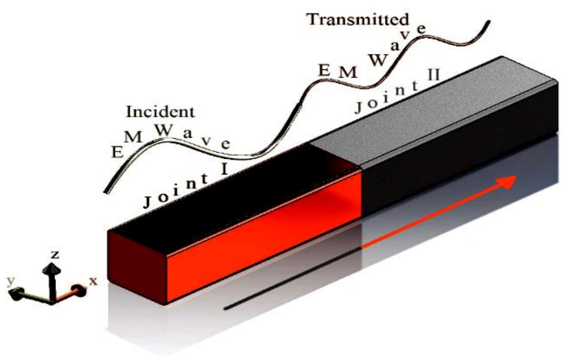

Fig. 2. Incident and transmitted EM waves (color online)

Eqs. (9, 10) represent the reflected and transmitted wave energies as Γ and T, respectively.

$$\Gamma = \left(\frac{k_m - k_{m+1}}{k_m + k_{m+1}}\right)^2 \tag{9}$$

$$T = 1 - \Gamma \tag{10}$$

It is assumed that there is a perpendicular transition when the EM wave passes from Joint I to Joint II, as depicted in Fig. 3. The figure also illustrates the travel of the reflected EM wave in Joint I.

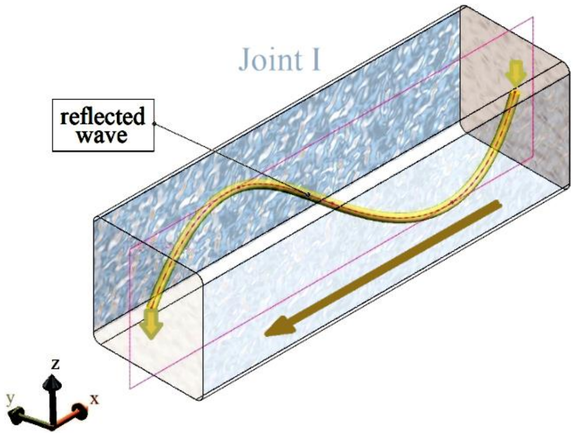

Fig. 3. Reflected EM wave (color online)

It is evident from Equations (9, 10) that if the material parameters (D_m) associated with Joint I and Joint II of the conjoined structure are identical, there are no reflections (Γ) present. In such cases, the EM wave can be transmitted entirely.

3. Results and discussions

The analysis of the electromagnetic frequency values of the conjoined carbon nanotube is presented in Figs. (4-6). A careful examination of Fig. 4 reveals that the propagation frequencies of the electromagnetic waves in the carbon nanotube decrease with the increasing nonlocal effects of "n".

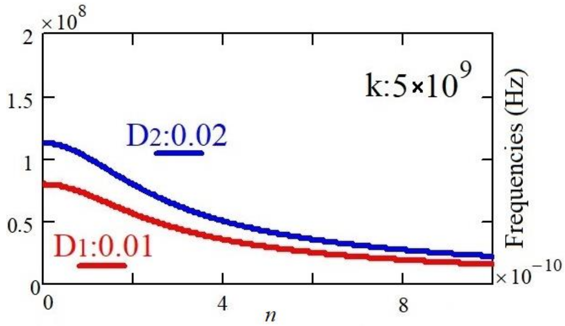

Fig. 4. Correlation between the nonlocal effects - EM wave propagation frequencies (n-ω) (color online)

The data presented in Fig. 5 indicates that higher material parameter *D* leads to a rise in electromagnetic wave propagation frequencies. However, both Fig. 4 and Fig. 5 demonstrate that non-local effects can lower the values of these frequencies.

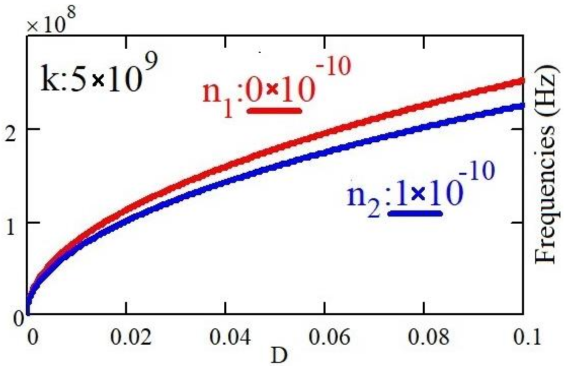

Fig. 5. Correlation between material parameters - EM wave frequencies (D-ω) (color online)

Upon examining Fig. 6, it becomes evident that the dispersion curves of EM wave propagation in the conjoined carbon nanotube structure are significantly impacted by nonlocal effects.

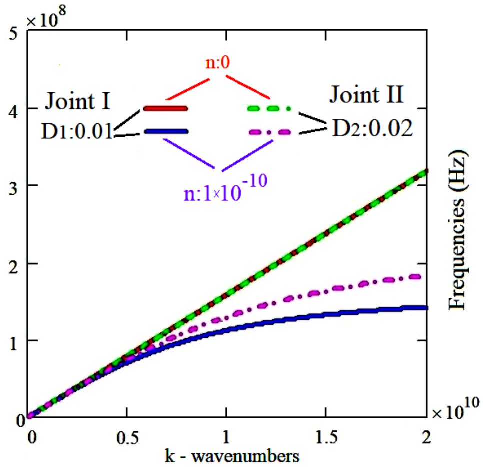

Fig. 6. Dispersion relation (k-ω) (color online)

The graph presented showcases an increase in the frequency values of EM wave propagation in both joints of the structure. It is worth noting that while the dispersion curves of the conjoined macro (non-nano) structure exhibit a linear increase, the EM wave propagation frequency values in the dispersion curves of the conjoined carbon nanotube structure display a decreasing slope.

The transition of the traveling wave from Joint I to Joint II is illustrated in Fig. 7, utilizing Eqs. (9,10). As the incident EM wave progresses in Joint I, a portion of it is transmitted to Joint II while the remaining travels in the opposite direction within Joint I, as demonstrated in Fig. 3. Upon analyzing the ratios of *D1/D2* material parameters presented in Fig. 7, it is discernible that reflection dominates when *D1* is more minor than *D2*. Conversely, when D1 is greater than *D2*, the transmittance of the EM wave decreases with an increase in the *D1/D2* ratio. As anticipated, the EM wave is entirely transmitted when *D1* and *D2* are equal.

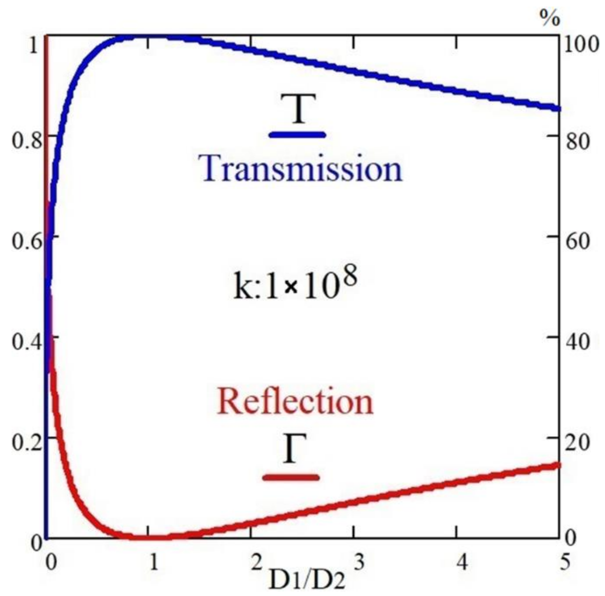

Fig. 7. The correlation between transmission and reflection based on the ratio of material parameter ratios (color online)

Fig. 8 depicts electromagnetic waveforms associated with EM wave propagation in a conjoined carbon nanotube under nonlocal effects. The EM wave is classified as incident, transmitted, and reflected waves, with their respective directions indicated by arrows in Figs. (8,9), while amplitude values (Amp.) are shown perpendicular to the direction of EM wave travel. In the case of the electromagnetic waves discussed in Figures (8,9), a transmission value of 97% was achieved by selecting $k = 5 \times 10^9$.

Fig. 9 showcases waveforms associated with electromagnetic wave propagation in the non-nano, conjoined macro structure. Notably, the frequencies of electromagnetic wave propagation occurring in the carbon nanotube are lower than those in the conjoined macro structure. Additionally, the figures demonstrate the seamless travel of the wave from Joint I to Joint II, highlighting the EM wave propagation in conjoined structures.

Overall, these results offer valuable insight into the behavior of electromagnetic waves in conjoined carbon nanotubes and macro structures under nonlocal effects, providing a foundation for future studies and applications in the field.

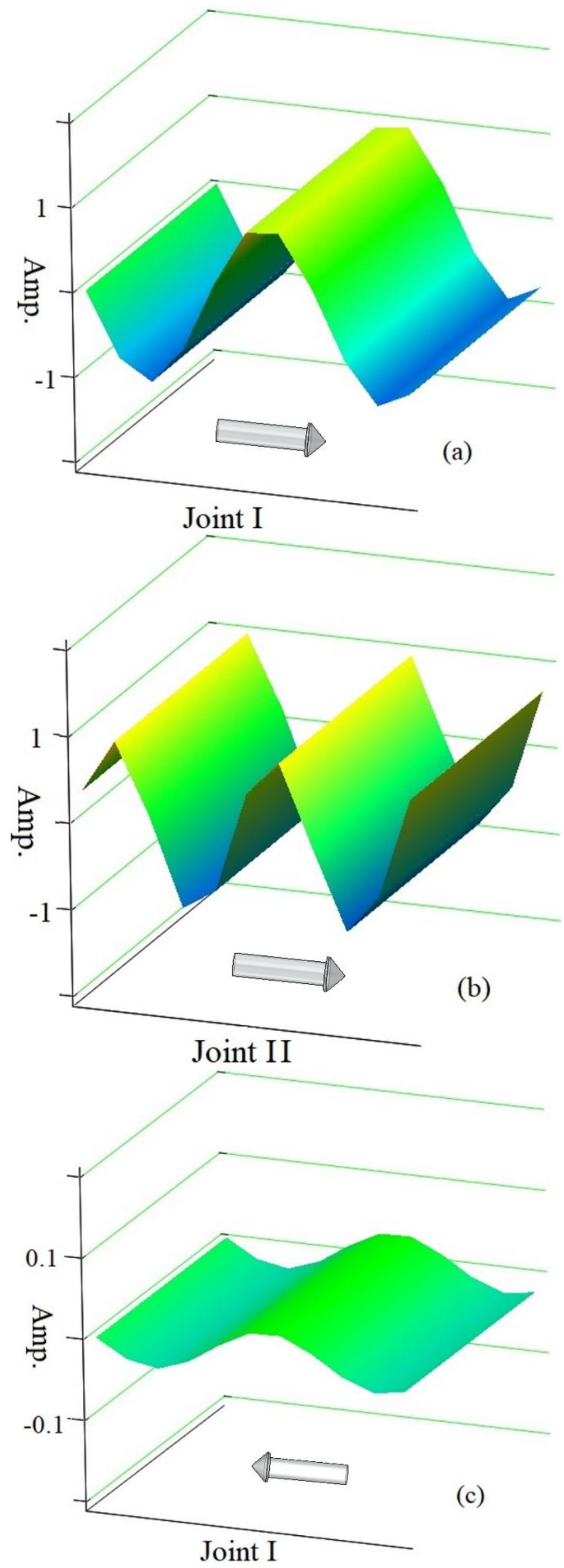

Fig. 8. Waveforms regarding EM wave propagation in the conjoined carbon nanotube, (a) the incident EM wave, (b) the transmitted EM wave, and (c) the reflected, backward EM wave (color online)

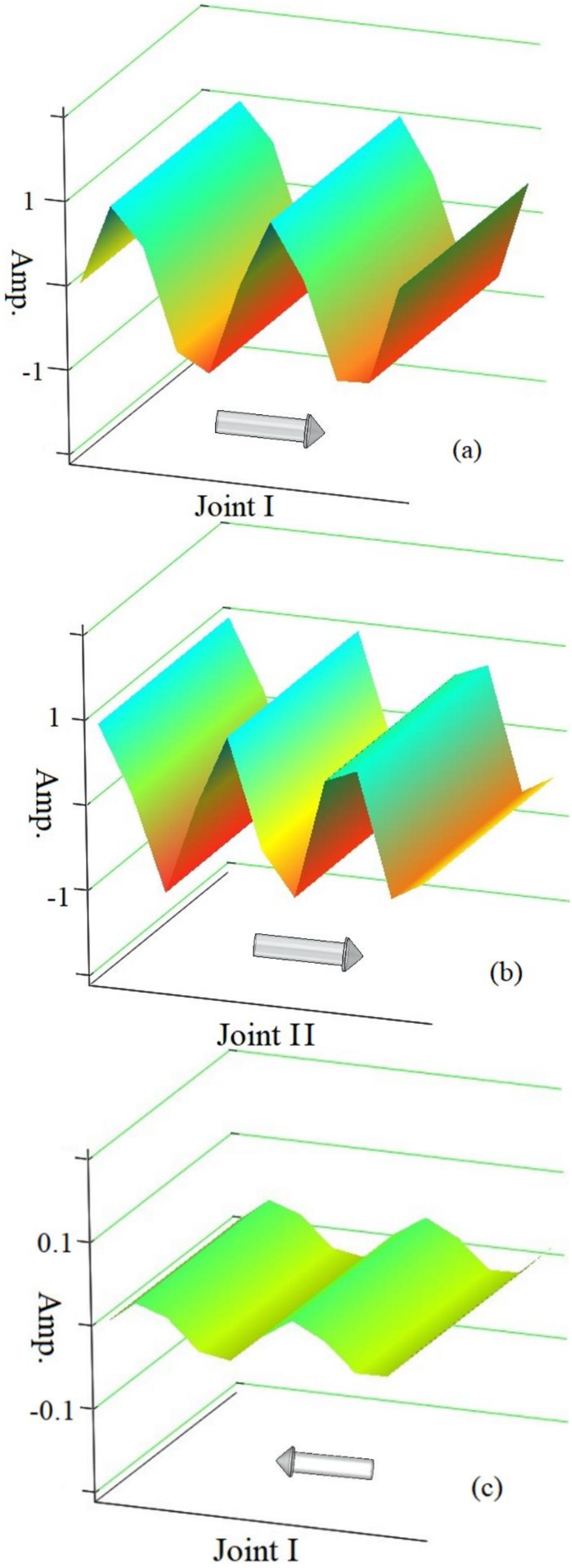

Fig. 9. Waveforms regarding EM wave propagation in the conjoined macro structure, (a) the incident EM wave, (b) the transmitted EM wave, and (c) the reflected, backward EM wave (color online)

4. Conclusions

In this study, the behavior of electromagnetic wave propagation in the conjoined carbon nanotube has been thoroughly investigated. By taking the material parameter ratio, $\frac{D_1}{D_2}$, as 0.5, the ratio of frequencies, $\frac{\omega_1}{\omega_2}$ related to electromagnetic wave propagation was found to be 1.41. It has been observed that this ratio remains constant even as the frequency values of electromagnetic wave propagation decrease due to "n" nonlocal effects. Furthermore, the frequency values of EM wave propagation in the structure decrease as "n" nonlocal effects increase. Interestingly, the frequency values of EM wave propagation for Joint I and Joint II of this bipartite conjoined carbon nanotube structure are identical.

This study is a unique contribution to the literature on the examination of EM waveforms in conjoined carbon nanotubes. It would be advantageous to explore the possibility of extending this analysis to encompass both two-dimensional and three-dimensional structures. This additional research could provide valuable insights and contribute to a more comprehensive understanding of the subject matter at hand.

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