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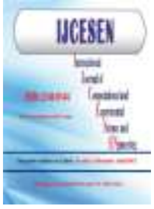

Investigation of Electromagnetic Wave Propagation in Nanocones

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Abstract:

The aim of this thorough study is to investigate the behaviour of electromagnetic wave propagation in three distinct nanostructures, each with unique shapes and material compositions. The first nanostructure under scrutiny is a butterfly-shaped nanocone formed by placing two nanostructures side by side. It consists of two nanocons. The second nanostructure is a deltoid-shaped nanocone created in a similar manner, composed of two different nanocones. The third nanostructure is a parallelogram-shaped nanocone constructed by stacking nanocones on each other and made of two different nanocones. These nanostructures differ in shape and material property parameters, each comprising two different materials with specific permeability and permittivity values. To conduct a detailed analysis, the study utilises the nonlocal theory to examine the electromagnetic wave propagation behaviour in these nanostructures. The focus of the analysis is on the travel and reflection of electromagnetic waves at three specific points along the same axis in each structure, allowing for a comprehensive comparison of their behaviours. This in-depth investigation holds significant importance as it seeks to understand the penetration and subsequent propagation of incident electromagnetic waves within nanostructures of varying shapes and material compositions, shedding light on their potential applications in advanced technology and optic science.

1. Introduction

The discovery of carbon nanotubes (CNTs) has revolutionised the study of nanostructures, leading to a surge in research on their behaviour and significance [1]. Nanostructures, such as carbon nanotubes, graphene, nanoballs, and nanocones, have played a pivotal role in the advancement of nanotechnology [2-5]. These structures are instrumental in the development of various technologies, including waveguides, filters, and photonic structures, which are frequently integrated into electro-optic and optical system designs. Over the past decade, there has been a widespread adoption of nano-optic and nanophotonic structures, reflecting their growing importance in modern technological applications [6-8]. Moreover, rapid advancements in material technology have fueled the exploration of new-generation materials aimed at enhancing the performance of optical and electro-optic systems. Carbon nanotubes and carbon nanotube-based structures are at the forefront of these developments, playing a crucial role in the design and enhancement of such materials. One of the most fascinating applications of these technological advancements is in stealth technology, where carbon nanotubes are utilised in the production of Radar Absorption Material (RAM). This technology involves coating the exterior of fighter aircraft with CNT-based paints to minimise their radar cross-section and evade detection [9-12]. This application showcases the significant impact of carbon nanotubes in shaping the future of advanced materials and technologies.

The use of new-generation metamaterials, which are engineered materials with properties not found in nature, allows for precise control and manipulation of electromagnetic wave propagation and frequencies. These metamaterials are designed to have specific values of permeability and permittivity, which are crucial in determining the direction of electromagnetic wave propagation [13-16]. Permeability refers to the material's ability to support the formation of magnetic fields, while permittivity relates to the material's ability to support the formation of electric fields. Together, these values influence whether the waves will be impeded or facilitated as they travel through the material. The behaviour of electromagnetic wave propagation in optical structures, such as photonic crystals, waveguides, and metamaterials, directly depends on these material property parameters. Photonic crystals are periodic dielectric structures that manipulate the flow of light, while waveguides guide electromagnetic waves along their length. Metamaterials, on the other hand, are artificially engineered materials designed to have electromagnetic properties not found in naturally occurring materials. Extensive literature has delved into exploring this intricate relationship, focusing on the design, fabrication, and characterisation of these new-generation materials and their impact on electromagnetic wave propagation and control [17-24]. In the analysis of nanostructures, the nonlocal theory is employed to examine the behaviour of electromagnetic wave propagation [25]. This theory elucidates that the propagation behaviour in nanostructures is influenced by the interactions of atoms in the immediate vicinity and those beyond at the atomic level. Furthermore, studies grounded in this theory can derive dispersion relations (k-ω) [26-29]. In this comprehensive study, the intricate behaviour of electromagnetic wave propagation in nanostructures, mainly focusing on nanocones and graphenes exhibiting butterfly, deltoid, and parallelogram shapes, is explored. The investigation elucidates the discernible variations in electromagnetic wave propagation behaviour within these nanostructures, stemming from their geometric diversity, material property discrepancies (including permittivity and permeability), and nonlocal properties arising from their intricate atomic structures. These nuanced differences serve as the cornerstone of the inquiry. To thoroughly explore the electromagnetic wave propagation behaviour, the intricate partial differential equations derived from Maxwell's equations are tasked with solving. For a detailed analysis of this solution, the insights from the scholarly works of Pozar and Cheng as guiding resources are meticulously referenced and drawn [30, 31].

2. Material and Methods

This thorough study examines how different nanocone shapes, such as butterfly, deltoid, and parallelogram, affect the propagation of electromagnetic waves. It also explores how material properties, specifically variations in material property parameters, impact the behaviour of electromagnetic wave propagation. The analysis begins with a focus on the nanocone, a structure that is symmetric with respect to the x-axis, which is the axis of electromagnetic wave propagation. The nanocone angle, denoted as θ, is set at 30˚, indicating the deviation angle from the x-axis. Furthermore, Figure 1 provides a visual representation of the electromagnetic wave propagation in a unit nanocone, offering a clear illustration of the studied phenomenon. Upon detailed examination of the incident electromagnetic wave, it is assumed to travel along three distinct paths: Path I, Path II, and Path III. These paths are depicted in figure 2, representing the assumed routes of the incident electromagnetic wave. As illustrated in figure 2, the behaviour of electromagnetic wave propagation is thoroughly examined in nanostructures with three distinct shapes: butterfly, deltoid, and parallelogram. It is important to note that the materials of the examined nanostructures are not monolithic; instead, they are deliberately selected to be distinctly different from each other. This entails the use of two different materials in each examined nanostructure, namely Material 1 (M-1) and Material 2 (M-2), further enriching the complexity of the analysis. The detailed analysis of these diverse nanostructures will contribute to a comprehensive understanding of the complex relationship between nanostructure geometry, material properties, and electromagnetic wave propagation. In a source-free, linear, isotropic and homogenous region, The first-order Maxwell’s curl equations are [30, 31]:

$$\nabla \cdot \vec{E} = 0, \qquad \text{(1a)}$$

$$\nabla \cdot \vec{H} = 0, \qquad \text{(1b)}$$

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

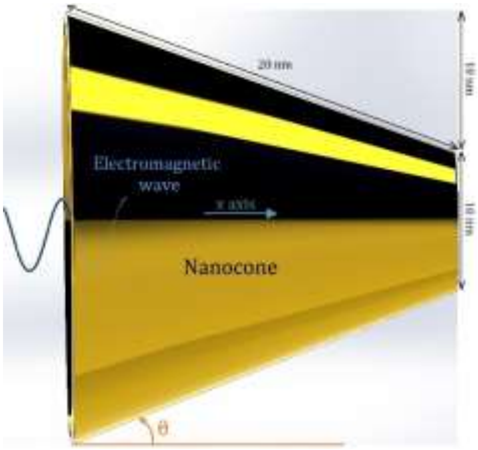

Figure 1. *Illustration of electromagnetic wave propagation in the unit nanocone.*

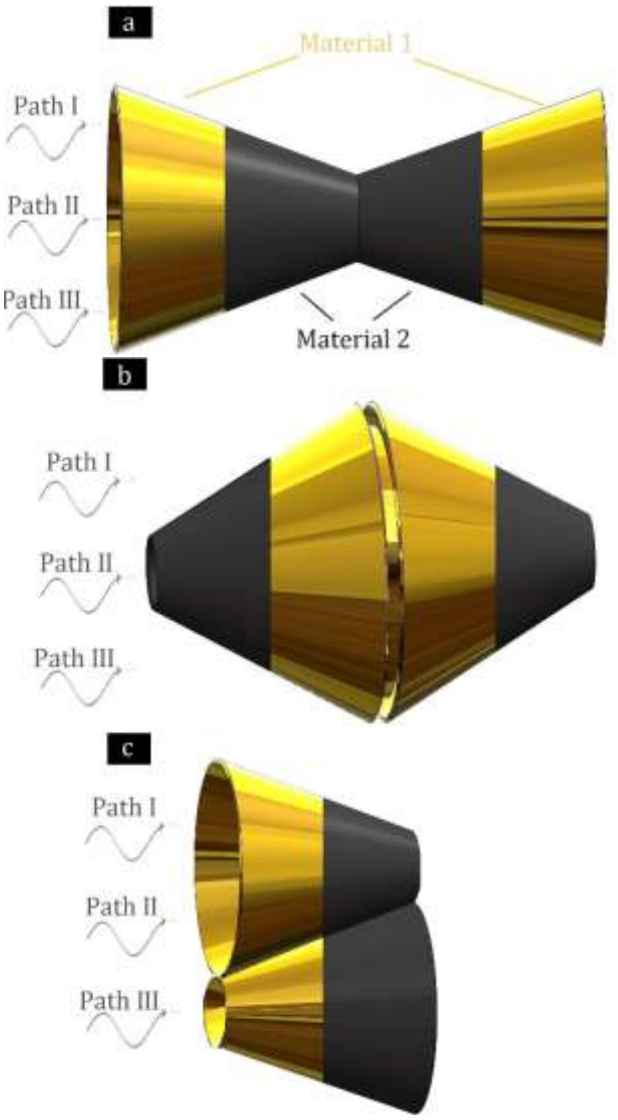

***Figure 2.** Schematic representations of the investigated nanocones, a) butterfly, b) deltoid and c) parallelogram.*

$$\nabla \times \vec{H} = i\omega\varepsilon \vec{E}. \qquad (1d)$$

where μ is the permeability, ε is the permittivity, $\vec{E}$ is the electrical field, and $\vec{H}$ is the magnetic field. Using Equ.s (1c) and (1d), Equ. (2) is obtained as follows:

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

Upon rearranging Equations (1a-1d), the equation describing electromagnetic wave propagation in a one-dimensional space along the x-axis can be obtained, expressed as Equation 3:

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

The displacement functions are utilised in the electromagnetic wave propagation equation derived in Equ. (3). It is essential to recognise that the term $i = \sqrt{-1}$ represents the imaginary unit in the given equations. The 1-dimensional electromagnetic wave equation (Equ. 2) is obtained through the application of Maxwell's equations Equ. (1a) and Equ. (1b). Consequently, the time-dependent equation for an electromagnetic wave propagating along the x-axis is derived.

If the equation for electromagnetic wave propagation (Equ. 2.3) is written as nonlocal [28]:

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

Here, *D* is the material property parameter. As the investigated nanostructures consist of two separate materials, M-1 and M-2, it is necessary to determine the material property parameters (D_1 and D_2) suitable for the nanostructures. In this study, the calculations are made assuming that the material property parameters of the nanostructures whose electromagnetic wave propagation behaviours are investigated are in the range of 0.01-0.5. Therefore, the material property parameters of the investigated nanocones are D_1:0.1 ve D_2:0.3, and the ratio between the material property parameters is D_1/D_2:0.333. The material property parameter *D*:1 is taken in the places where the electromagnetic wave exits the nanocone. In addition, $\eta = e_0 a$ is the nonlocal parameter.

The electromagnetic wave (EMW) propagation field of the investigated nanocone is represented by *w(x,t)*. The propagation equations for the incident (w_i), transmitting (w_t), and reflecting (w_r) electromagnetic waves are as follows:

$$H_{1_x} = w_i e^{i(\omega t - k_1 x)} + w_r e^{i(\omega t + k_1 x)}, \qquad (5a)$$

$$H_{2_x} = w_t e^{i(\omega t - k_2 x)}. \qquad (5b)$$

Upon substituting Equ. 5a and Equ. 5b into Equ. 4, the solution for obtaining the electromagnetic frequencies (ω) can be derived. It is noteworthy that while the incident and reflected electromagnetic waves propagate within the same material (M-2), the transmitted wave continues its propagation within the M-2 material. Equ. 5a pertains to the propagation in the M-1 material, whereas Equ. 5b pertains to the propagation in the M-2 material. The variables H_{1_x} and H_{2_x} represent the electromagnetic wave in M-1 and the displacement fields of the transmitted electromagnetic wave in M-2, respectively. The wave number, denoted as k, encompasses k_1 representing the wave number in M-1 and k_2 representing the wave number in M-2. Furthermore, the reflection (Γ) and transmission (*T*) rates associated with electromagnetic wave propagation in nanocones are specified as follows:

$$T + \Gamma = 1, \qquad \text{(6a)}$$

$$\Gamma = \left[\frac{k_2 \cos(\theta_t) - k_1 \cos(\theta_i)}{k_2 \cos(\theta_t) + k_1 \cos(\theta_i)} \right]^2 . \qquad \text{(6b)}$$

Here, θ_i denotes the angle of the incident wave, representing the angle difference with the interface, while θ_t represents the angle of the transmitted wave. In figure 3, the angle values for the transmission of electromagnetic waves (EMWs) between materials m and n, characterised by the material property parameters D_m and D_n, are presented.

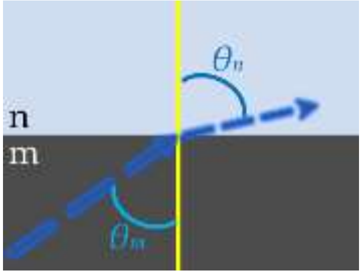

Figure 3. *The angle of an EMW as it passes through a different material.*

The angle value for material m is denoted as θ_m, representing the angle formed by the incident wave as it enters material m. Similarly, the angle value for material n is denoted as θ_n, signifying the angle at which the wave is refracted upon entering material n. As illustrated in Figure 3, the incident wave undergoes refraction, forming an angle with the normal, which is determined by the material properties and the incident angle of the electromagnetic wave. This phenomenon is elucidated by Snell's law, which describes the relationship between the angles of incidence and refraction as the electromagnetic wave passes through the interface between the two materials [32,33] as follows:

$$D_m \sin\theta_m = D_n \sin\theta_n \qquad (7)$$

Examining all the nanocone structures, it is assumed that the incident waves enter the structures perpendicularly to the surface. It should be noted that these nanocones form an angle of θ degrees (conic angle) with the surface due to their shapes. Consequently, these angle factors have a notable impact on the transmitted wave. This particular aspect constitutes a novel contribution to the existing literature.

3. Results and discussion

As depicted in figure 4, the electromagnetic wave traverses nine paths in three nanostructures. While the incident waves in butterfly and parallelogram-shaped nanocones initially propagate from M-1, in the deltoid-shaped nanocone, the incident wave commences its propagation from the M-2 material.

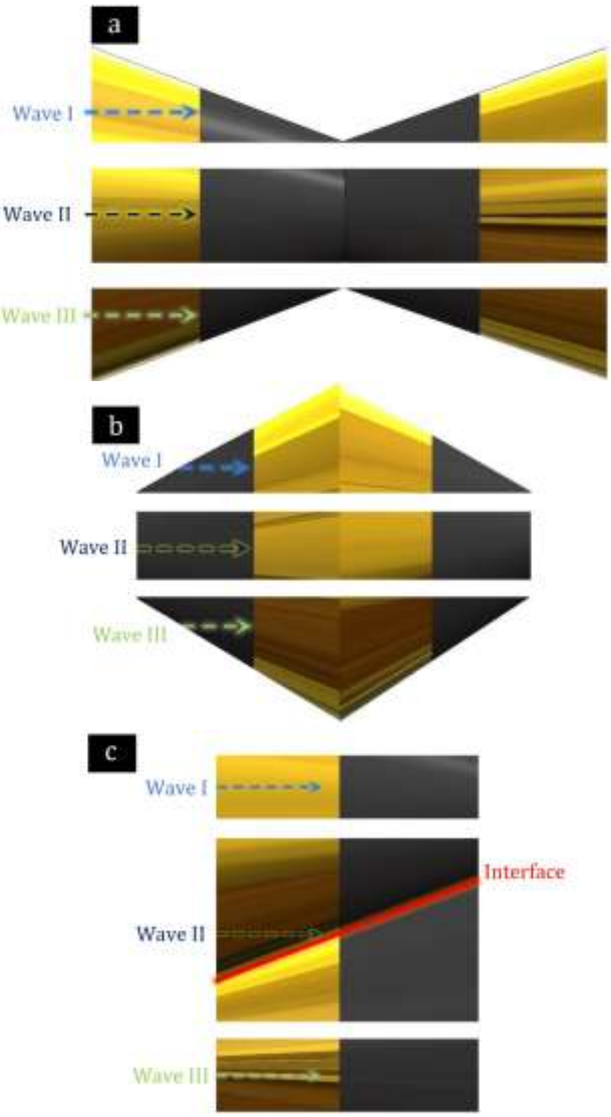

Figure 4. *Electromagnetic wave propagation paths in the nanocones are a) butterfly-shaped, b) deltoid-shaped, and c) parallelogram-shaped.*

Furthermore, it is postulated that the three distinct electromagnetic waves (Wave I, Wave II And Wave III) do not exhibit any overlap.In figure 4, it can be observed that the electromagnetic wave is transmitted without being affected by the shape of the deltoid-shaped nanocone structure, meaning there is no change in angle. In the parallelogram-shaped nanocone structure, the electromagnetic wave propagates without disruption, similar to the deltoid-shaped nanocone. However, in the parallelogram-shaped nanocone structure, a disruption, i.e., an angle change, is observed at the interface section. Another observation is that in the butterfly-shaped nanocone structure, the electromagnetic wave propagating in the M-1 section is refracted and propagates outside the material. As for the butterfly-shaped nanocone structure, the wave propagating in the M-2 section is the reflecting electromagnetic wave. The impact of the reflecting electromagnetic wave is limited. Furthermore, the behaviour of electromagnetic wave propagation is examined with the assumption that the transmitted waves do not overlap and that each path is a separate region. Therefore, the waves originating from the nanocones and the paths in which they are located are disregarded. Additionally, in the studies conducted, the nonlocal parameter η:1 is considered in nanostructures. The angles at which incident electromagnetic waves are transmitted for different ratios of material property parameters (D_1/D_2 or $D_{incident}/D_{transmitted}$) are shown in figure 5. As this ratio increases, the transmitted electromagnetic wave angles (θ_t) also increase. In figure 6, the butterfly-shaped nanocone structure induces scattering in electromagnetic waves denoted as Wave I and Wave III, thereby impeding their propagation throughout the structure. Notably, the outer plane's material property parameter, governing the trajectory of the scattered electromagnetic wave, is stipulated as 1. Electromagnetic waves are transmitted and propagated through the deltoid-shaped nanocone illustrated in figure 7 and the parallelogram-shaped nanocone presented in figure 8. In the deltoid nanocone structure, transmission is facilitated along all three pathways, resulting in transmission characteristics that are observed to occur at uniform rates.

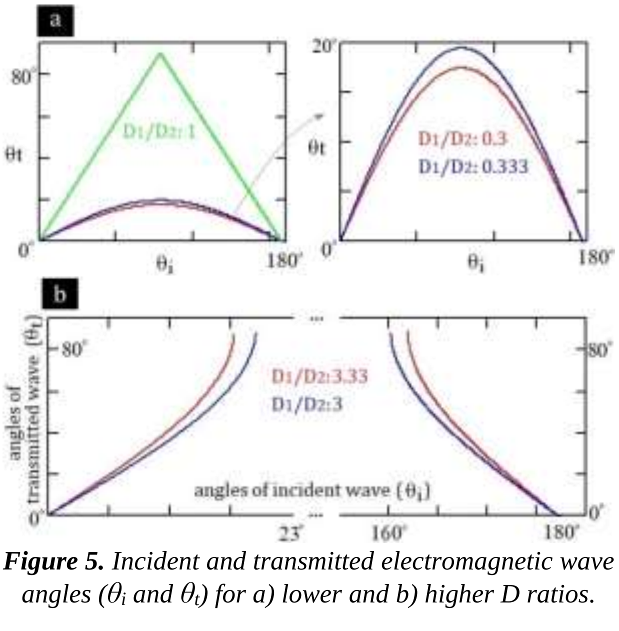

Figure 5. *Incident and transmitted electromagnetic wave angles (θ_i and θ_t) for a) lower and b) higher D ratios.*

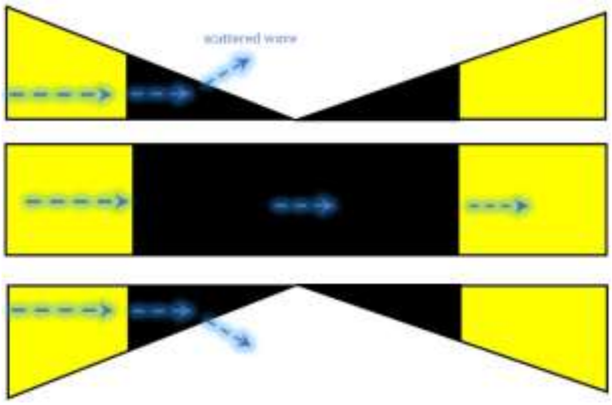

Figure 6. *Electromagnetic wave propagation in butterfly-shaped nanocone.*

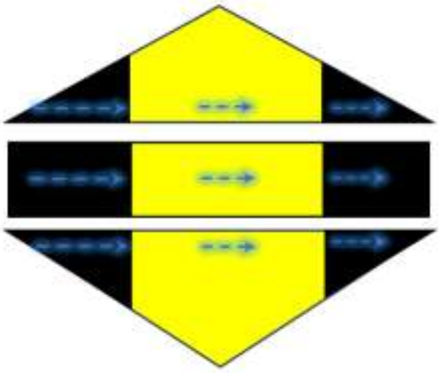

Figure 7. *Electromagnetic wave propagation in deltoid nanocone.*

In the parallelogram-shaped nanocone depicted in figure 8, the electromagnetic wave exhibits similar behaviour in Path I and III. Additionally, the characteristics of electromagnetic wave propagation along these paths closely resemble those in the butterfly-shaped nanocone. However, when examining wave propagation in Path II of the parallelogram-shaped nanocone, it is observed that the electromagnetic wave, referred to as Wave II, is refracted at the interface. When analysing the electromagnetic wave along Path 2, as illustrated in figure 8, it is observed that the wave arrives at the interface at an angle of θ_i:60° and refracts at an angle of θ_t:15°. The transmission ratio for this electromagnetic wave is calculated to be T:0.51, as derived from Equ.s (6a, 6b). This finding represents a critical aspect of this study.

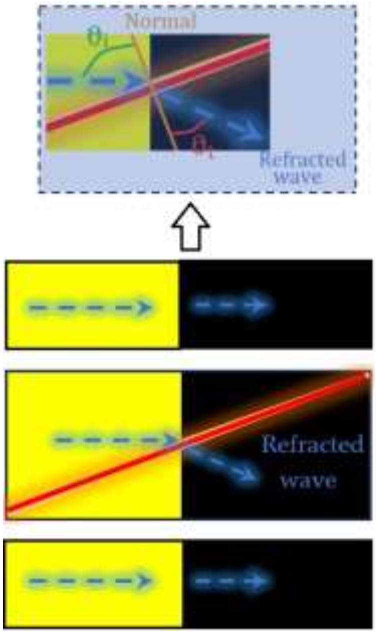

***Figure 8.** Electromagnetic wave propagation in parallelogram-shaped nanocone.*

In comparison, when the electromagnetic wave approaches the interface perpendicularly, the transmission ratio is determined to be 0.75. Consequently, it is essential to recognise that the electromagnetic waves traveling along Paths 1 and 3, as depicted in figure 9, are transmitted to M-2 with a transmission ratio of T:0.75. The scattered electromagnetic waves that escape the structure are excluded from the calculations, as they do not contribute to the overall transmission. The transmission ratio for electromagnetic waves transmitted from M-1 to M-2 or vice versa is also found to be 0.75. Through the analysis conducted for Path 2 in both butterfly-shaped and deltoid-shaped nanocones, the transmission ratio for the electromagnetic waves reaching the terminus of the nanocones is established at 0.56. In the deltoid-shaped nanocone structure, this transmission ratio consistently measures 0.56 across all paths. Figure 9 presents the dispersion relations (k-ω) for the electromagnetic wave propagation. In figure 9a, the influence of various material property parameters and wave numbers (k) on the electromagnetic wave propagation frequency is portrayed. It can be concluded that at elevated wave numbers (k), the propagation frequencies stabilise at a constant due to the nanoscale dimensions of the examined structures, characterised by a nonlocal constant of (η:1) [28]. Figure 9b offers a comparative analysis of the electromagnetic wave propagation frequencies in nonlocal nanoscale structures versus local non-nanoscale structures, thereby investigating the effect of wave numbers (k) on these frequencies. As anticipated, in the nonlocal nanoscale structure, the frequency values (ω) exhibit an increase in correlation with the increase in wave numbers (k).

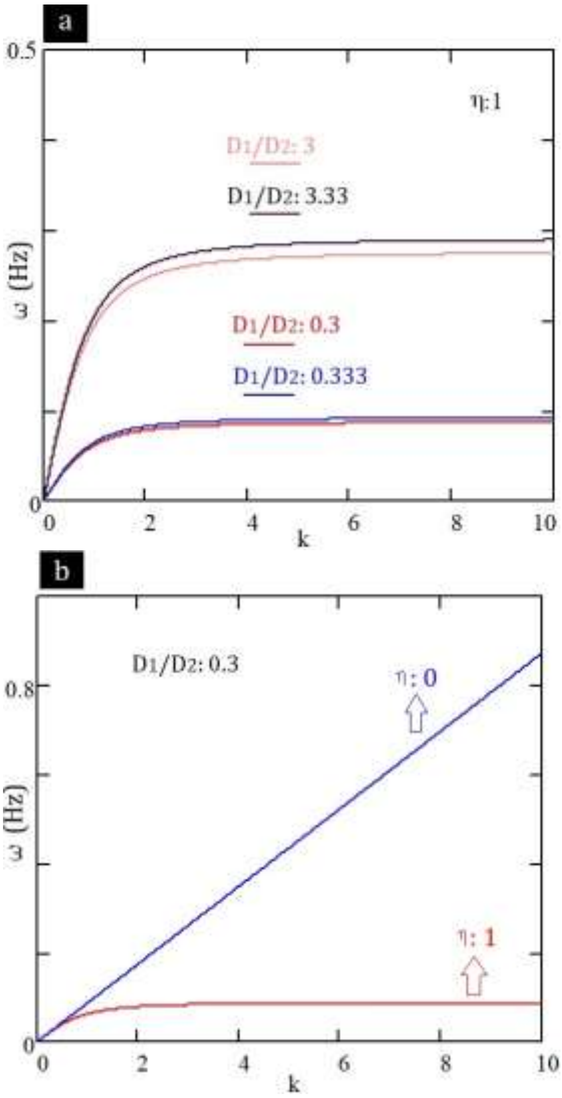

***Figure 9.** Dispersion relations, a) due to the various material property parameter ratios (D) and b) due to the comparison of local (η:0) - nonlocal (η:1) conditions.*

4. Conclusions

This study provides a comprehensive analysis of electromagnetic wave propagation within three distinct nanocone structures: deltoid-shaped, butterfly-shaped, and parallelogram-shaped. The primary objective is to assess how the geometry of these nanocones influences electromagnetic wave transmission and to determine whether these structures facilitate wave propagation along the x-axis. Although the electromagnetic waves were incident perpendicularly upon the nanocone configurations, evidence indicated that scattering occurred as a result of the conical shapes. This scattering phenomenon led to a diminished effectiveness of the waves. Notably, the butterfly-shaped nanocone demonstrated the most significant scattering of electromagnetic waves. Conversely, the parallelogram-shaped nanocone enabled electromagnetic waves to transition from one material (designated as M-1) to another (designated as M-2), a behavior that was not observed in the butterfly-shaped structure.

Future investigations could focus on the examination of electromagnetic wave propagation in various nanoscale or non-nanoscale structures, such as carbon nanotubes and graphene, as well as nanocones oriented at varying angles, employing the methodology established in this study. Additionally, researchers may explore the propagation characteristics of overlapping electromagnetic waves, particularly investigating the behaviors of backward electromagnetic waves that are subject to reflection.

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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- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **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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