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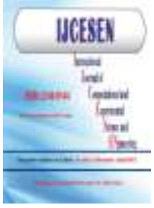

Research Article

Electromagnetic Wave Propagation in Photonic Nanoplates

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Abstract:

In this study, an investigation into the behaviour of electromagnetic wave propagation in a nanoplate, utilizing Eringen’s model, which is rooted in nonlocal theory, is conducted. This model accounts for the interaction of atoms that are at a significant distance from each other. The objective of this study is to derive solutions that incorporate both local and nonlocal calculations. The focus of this study revolves around the material property parameter values of the nanoplate and the impact of nano coefficients (nonlocal parameters) on the electromagnetic wave propagation behaviour. Additionally, the frequency and wave amplitude values of the electromagnetic wave propagation are determined. By implementing Eringen’s model, a comprehensive understanding of how electromagnetic waves traverse a nanoplate, considering the influence of nano coefficients on the electromagnetic wave propagation behaviour, and identifying the frequency and amplitude of the electromagnetic waves as they propagate through the nanoplate is explored. The solutions encompass both local and nonlocal calculations are aimed to derive. By using this model, a solution that accounts for both local and nonlocal calculations and examines how electromagnetic waves travel through a nanoplate, the effect of nano coefficients on electromagnetic wave propagation behaviour, and the frequency and amplitude of the electromagnetic waves as they propagate through the nanoplate is obtained.

1. Introduction

After the discovery of carbon nanotubes, a new frontier has been reached in the field of nanomaterials, paving the way for new opportunities for researchers [1]. Following the invention of these nanoscale structures, in-depth studies have been conducted in optics using these nanomaterials [2, 3]. Electromagnetic (EM) shielding technology, also referred to as stealth technology, is a specialised area of research that involves the use of materials to facilitate high attenuation and low reflection of electromagnetic waves [4-7]. Researchers have undertaken substantial investigations into photonic crystals and optical structures based on these electromagnetic principles [8-14]. Furthermore, the literature contains detailed analyses of reflection and transmission concepts related to the propagation of electromagnetic waves in photonic structures [15, 16].

Carbon nanotube-based structures are commonly utilised for the absorption of radar beams during the shielding process, leveraging the permittivity and permeability of carbon nanotubes to effectively protect against electromagnetic waves. These nanotubes are categorised as single-walled (SWCNT) and multi-walled (MWCNT) and have been the subject of extensive study using both theoretical and experimental methods [17-21]. Additionally, a theoretical analysis of the behaviour of electromagnetic wave propagation in double-walled and triple-walled carbon nanotubes is detailed in [20-22].

In a 2-dimensional macro photonic crystal, waveforms occurring at different angles and the transmission/reflection properties of electromagnetic waves as they propagate through mediums with different material property parameters have been investigated [23]. Another study has examined the propagation of electromagnetic waves in a macro plate [24]. This study has used a holistic approach to evaluate the plate's inner and outer parts nodally, revealing different material property parameters at each node point. It has determined the electromagnetic wave propagation frequencies using the finite difference method.

In this study, the electromagnetic wave propagation behaviour exhibited by the electromagnetic wave propagating along the x and y axes in the nanoplate and the macro plate is investigated. This study differs from other studies in the literature in that it comparatively examines the properties of the electromagnetic wave propagating along both the x and y axes. While a part of the electromagnetic wave continues to propagate along the x-axis, following the nanoplate and macro plate, respectively, the electromagnetic wave propagating in the y-axis continues to propagate along the y-axis without encountering a different material property parameter or nano coefficient (nonlocal parameter). Therefore, it is possible to propagate without changing its form. In this study, this deficiency in the literature is eliminated by examining the different propagation situations of the electromagnetic wave along two axes in the sense of novelty.

2. Material and Methods

The research conducted a comprehensive analysis of the electromagnetic wave propagation behaviour in both the nanoplate and macro plate segments of a plate. Figure 1 depicts the propagation of electromagnetic waves within a plate.

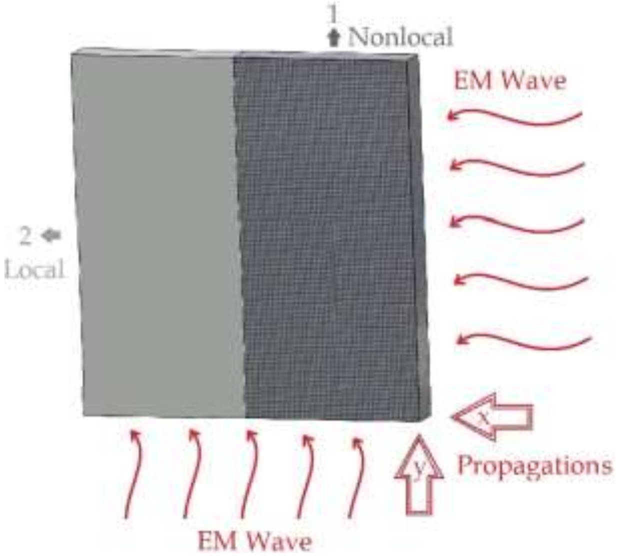

Figure 1. *Electromagnetic (EM) wave propagation in the plate.*

One section of the plate is nano-sized with a nonlocal parameter of η, while the other is macro-sized. Thus, the structure under examination represents a partial nanostructure, as indicated in the figure. The properties of electromagnetic wave propagation along the x and y axes in this 2-dimensional plate are being separately analysed.

Maxwell's equations, which examine the propagation of electromagnetic waves, are expressed as follows in the effect of a linear, isotropic, and homogeneous region that is free from sources [22]:

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon}, \qquad (1a)$$
$$\nabla \cdot \vec{H} = 0, \qquad (1b)$$
$$\nabla \, \mathrm{x} \, \overrightarrow{E} = -\mathrm{i}\omega\mu\overrightarrow{H}, \qquad (1c)$$
$$\nabla \, \mathrm{x} \, \overrightarrow{H} = \mathrm{i}\omega\varepsilon\vec{E}. \qquad (1d)$$

where E refers to the electric field, H denotes the magnetic field, ε is the electric permittivity, μ denotes the magnetic permeability, ρ is the charge density, and i is the imaginary number. The dot product (·) is also known as the scalar product, and the cross product (x) is also known as the vector product.

Upon rearranging Equations (1a-1d), the equation describing electromagnetic wave propagation in a one-dimensional space along the x or y axis can be obtained, expressed as Equation 2:

$$\frac{1}{\mu\varepsilon}\frac{\partial^2 H_\alpha}{\partial\alpha^2} - \frac{\partial^2 H_\alpha}{\partial t^2} = 0 \qquad (2)$$

Here, α represents a single axis; H_α denotes the magnetic field vector along that axis.

The material property parameters (μ, ε) of a reference point in a nanostructure influence the material properties of nearby points. According to Eringen's non-local theory, the material property parameters (μ, ε) of this reference point also affect the material properties of all non-local points that are not neighboring this region. Consequently, the electromagnetic wave equation of nanostructures can be expressed as follows [18-22]:

$$D_n \frac{\partial^2 H_x}{\partial x^2} = \left[1 - \eta^2 \frac{\partial^2}{\partial x^2}\right] \frac{\partial^2 H_x}{\partial t^2} \qquad (3a)$$
$$D_m \frac{\partial^2 H_x}{\partial x^2} = \frac{\partial^2 H_x}{\partial t^2} \qquad (3b)$$

where $D_n = 1/(\mu_n \varepsilon_n)$ and $D_m = 1/(\mu_m \varepsilon_m)$ represent material property parameters, and η represents the nonlocal parameter. The variables n and m represent the nanoscale and macroscale components, respectively, in the context of the plate. This study focuses on the behaviour of electromagnetic wave propagation in the plate along the x and y axes.

Consequently, the expression for electromagnetic wave propagation along the y-axis is as follows:

$$D_n \frac{\partial^2 H_y}{\partial y^2} = \left[1 - \eta^2 \frac{\partial^2}{\partial y^2}\right] \frac{\partial^2 H_y}{\partial t^2} \qquad (4a)$$

$$D_m \frac{\partial^2 H_y}{\partial y^2} = \frac{\partial^2 H_y}{\partial t^2} \qquad (4b)$$

The investigation employs a comprehensive evaluation approach that entails the utilisation of specific material parameters [17]. These parameters, denoted by D values, have been meticulously selected from a plate spectrum. Specifically, $D_n: 0.05$ is allocated for the nanomaterial segment of the plate, while $D_m: 1$ is designated for the macro material segment.

The expressions for the electromagnetic displacements of incident electromagnetic waves, denoted by H_x and H_y can be represented in the following forms:

$$H_x = he^{\mathrm{i}(\omega t - kx),} \qquad (5a)$$

$$H_y = he^{\mathrm{i}(\omega t - ky).} \qquad (5b)$$

Equations (5a, 5b) encompass three variables: h denotes the travelling wave, ω represents the frequency of electromagnetic wave propagation, and k represents the wave number.

Upon applying Equations (5a, 5b) to Equations (3a – 4b), the frequency values for electromagnetic wave propagation in the nanoplate can be obtained as expressed in Equation 6. It is evident from Equation 6 that the frequency values for electromagnetic wave propagation are contingent upon D_n and η.

$$\omega = \frac{\sqrt{D_n (1 + {k_n}^2 \eta^2) k_n}}{(1 + {k_n}^2 \eta^2)} \qquad (6)$$

In the present study, it is observed that the electromagnetic wave propagates along the axis without changing its angle. Consequently, the transmission T and reflection Γ coefficients of the electromagnetic wave transmitted from the nanoplate to the macro plate are as follows:

$$T + \Gamma = 1, \qquad (7a)$$

$$\Gamma = \frac{(k_m - k_n)^2}{(k_m + k_n)^2}. \qquad (7b)$$

In the given context, k_n denotes the wave number in the nanoplate, while k_m denotes the wave number in the macro plate.

The waveform of the electromagnetic wave changes as it transitions from the nanoplate (n) to the macro plate (m) along the x-axis. However, the waveform of the electromagnetic wave propagating along the y-axis remains unchanged as it continues its propagation.

3. Results and Discussions

The data obtained from the calculations on electromagnetic wave propagation provides detailed insights into the behaviour of electromagnetic waves. Figure 2 illustrates the reflection and transmission rates for electromagnetic wave propagation in the plate.

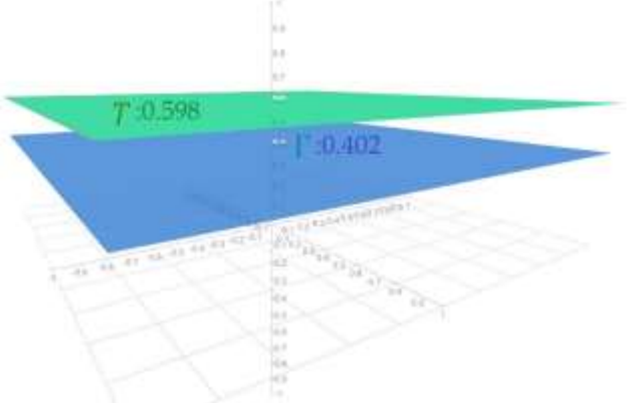

Figure 2. *Reflection and transmission ratios related to the nanoplate.*

The computations have yielded two significant outcomes. Firstly, it has been ascertained that the incident electromagnetic wave is directly influenced by the material property parameter D_n and the nonlocal parameter η in the propagation of electromagnetic waves within the nanoplate. Additionally, it has been inferred that the sole influencing factor in the wave propagation within the plate is the material property parameter D_m, given the nonlocal parameter's value of $\eta: 0$ in the macro plate.

It is evident from Equations (3a, 3b) that the electromagnetic wave propagates along the x-axis from the nanoscale component to the macroscale component of the plate, while Equations (4a, 4b) indicate wave propagation along the y-axis. This suggests a lack of transmittance and reflectance, thereby impacting the reflection and transmission ratios in the plate. The analysis focuses on the propagation of electromagnetic waves along the x-axis, utilising Equation (6) derived from Equations (3a, 3b, 5a, 5b).

Figure 3 illustrates the waveform of the incident electromagnetic wave within the nanoplate, while Figure 4 displays the waveform of the reflected electromagnetic wave. It is significant to note that the amplitude of the reflected electromagnetic wave is smaller than that of the incident electromagnetic wave.

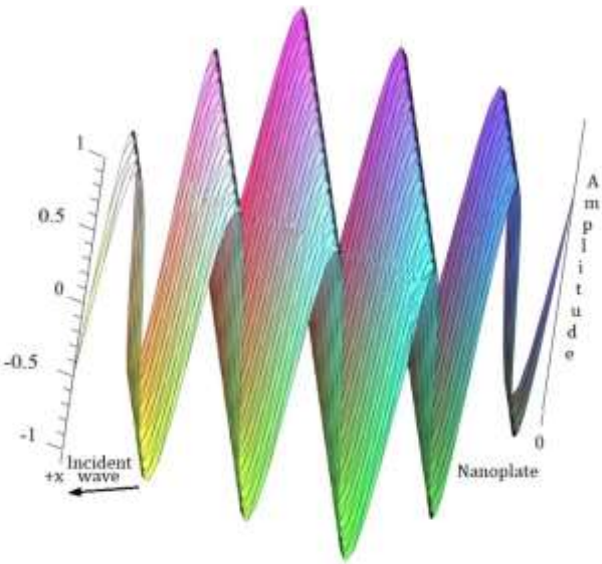

Figure 3. *The waveform of the incident EM wave propagating through the nanoplate along the x-axis.*

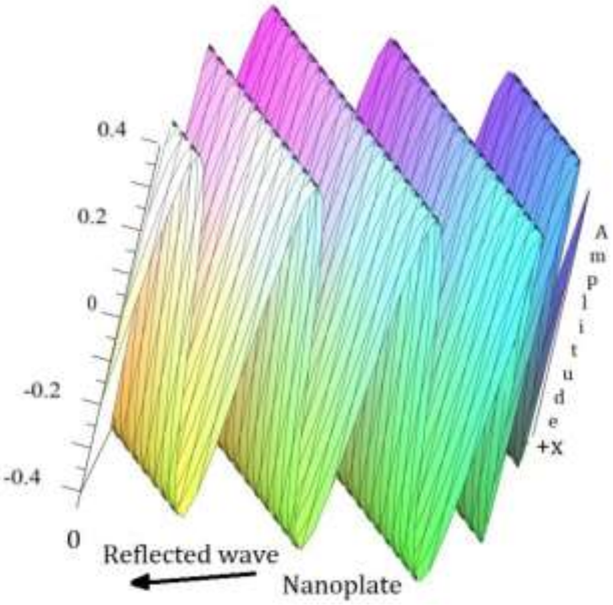

Figure 4. *The waveform of the EM wave propagates and reflects in the nanoplate along the x-axis.*

This disparity in amplitude indicates a reduction in the strength of the reflected wave in comparison to the incident wave, thus bearing implications for the behaviour of the electromagnetic wave within the nanoplate.

The waveform of the electromagnetic wave transmitted from the microplate to the macro plate is depicted in figure 5. Additionally, it is noteworthy that the frequencies of electromagnetic wave propagation in the nanoplate are observed to be lower than those in the macro plate, suggesting a disparity in electromagnetic wave behaviour between the two plates.

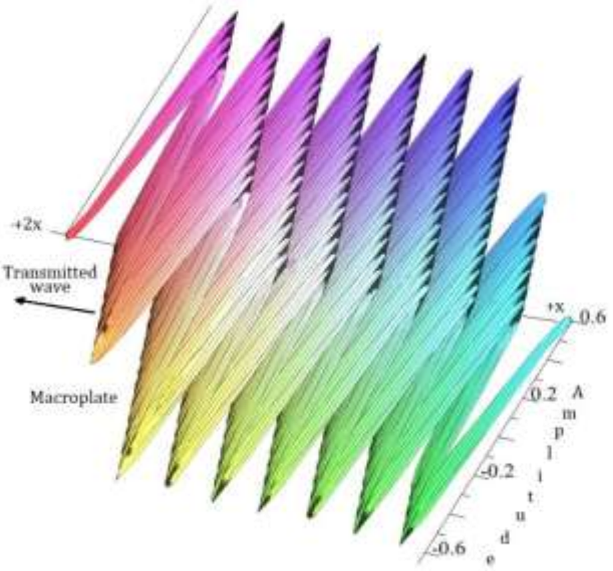

Figure 5. *The waveform of the transmitted electromagnetic wave propagating through the makro plate along the x-axis.*

It is important to note that the frequency values associated with electromagnetic wave propagation in the nanoplate are lower than those associated with electromagnetic wave propagation in the macro plate. As the electromagnetic wave travels along the y-axis, it does not transition between the nanoscale and macroscale parts of the plate. Therefore, the discussion of wave transmission or reflection is not applicable in this case. The waveform of the electromagnetic wave propagating along the y-axis is illustrated in Figure (6,7).

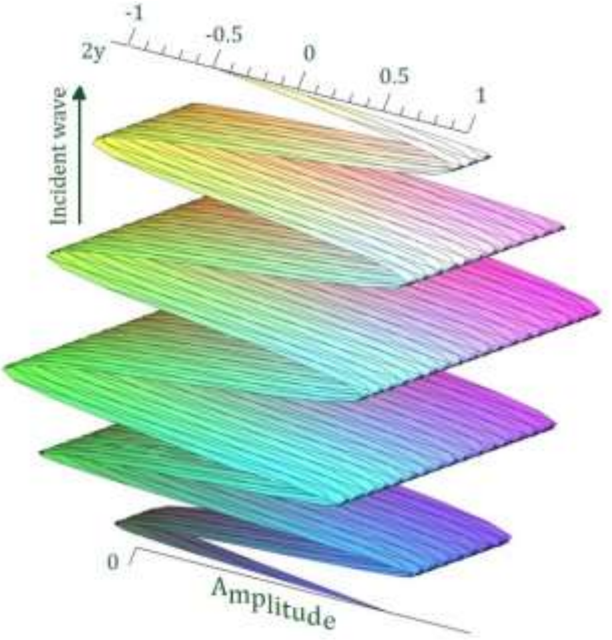

Figure 6. *The waveform of the incident electromagnetic wave propagating through the nanoplate along the y-axis.*

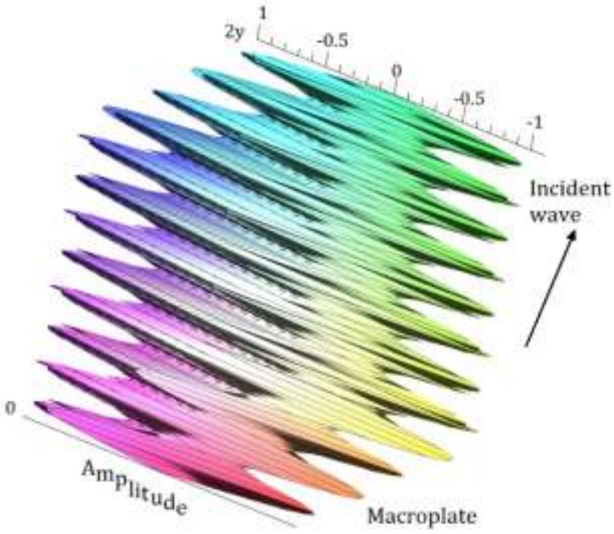

Figure 7. *The waveform of the incident electromagnetic wave propagating in the macro plate along the y-axis.*

4. Conclusions

The study examined the behaviour of electromagnetic wave propagation in both the nanoplate and macro plate segments of a plate. During the examinations, $D_m: 1$ was utilised for the macro plate, and $D_n: 0.05$ was employed for the nanoplate. The following conclusions were derived from the examinations:

- The presence of the nonlocal parameter or nano coefficient (η) in nanoplates diminishes the frequency values of electromagnetic wave propagation. This deduction is discernible from the waveforms obtained (refer to Figures 3, 4, and 6),
- The waveforms related to electromagnetic wave propagation in the macro plate are only affected by D_m. Since $\eta: 0$ in this case, it was observed that the frequency values of electromagnetic wave propagation in the macro plate were higher than those in the nanoplate (refer to Figure 5, 7).

The methodology employed in this study holds promise for future research endeavours aimed at investigating the electromagnetic wave propagation behaviour in nanostructures at varying angles.

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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